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WORKSHOP :

Applications of

SQUID

Magnetometrie

INSA de Lyon
16 et 17 juin 1999
Lyon - France

19991105 103

Professor Pierre-Louis VUILLERMOZ wishes to thank the following for their contribution to the success of this conference :

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298-102

**Introduction to SQUID Magnetometry
and Its Applications**
(plus some examples of the author's research)

**Harold Weinstock
US Air Force Office of Scientific Research
Arlington, VA 22203-1977 USA**

**Workshop on Applications of SQUID Magnetometry
INSA de Lyon
Lyon, FRANCE
June 16-17, 1999**

DTIC QUALITY INSPECTED 4

APPLICATIONS OF SQUID MAGNETOMETRY

(TOPICS TO BE COVERED)

Commercialization of SQUIDS

NDE of engineering structures and wires

RF amplifiers and dynamics of magnetic bacteria

Geophysical exploration

Magnetoencephalography (MEG)

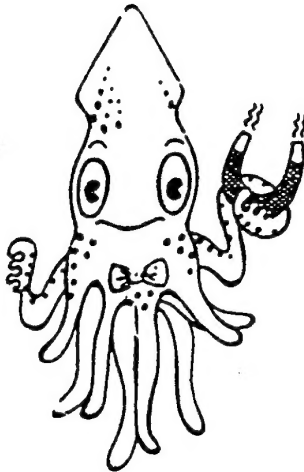
Magnetocardiography (MCG)

Liver susceptometry and intestinal ischemia

SQUID

Superconducting Quantum
Interference Device

$$\Phi_0 = 2.07 \times 10^{-15} \text{ Wb} = \frac{h}{2e}$$



Squid, *Ommastrephes sagittatus*

Typical sensitivity $\approx 10^{-4} \Phi_0$
or $\approx 1-10 \text{ fT/Hz}^{1/2}$
(commercial instruments)

ALTERNATIVE MAGNETOMETERS

- Variometer

Rotation of a suspended magnet
 10^{-10} THz $^{-1/2}$ at zero frequency

- Fluxgate 10^{-10} THz $^{-1/2}$ DC to kHz

- Induction Coil

10 cm long, 10 cm diameter
 10^{-13} THz $^{-1/2}$ at 10 Hz at room temperature
 10^{-13} THz $^{-1/2}$ at 4 K

- Magnetic resonance magnetometers

- Hall effect

- Optical fiber

- SQUID 10^{-14} THz $^{-1/2}$ DC to 10's of kHz

"Magnetic quantities, units, materials and measurements," J.E. Zimmerman, in *Biomagnetism: an Interdisciplinary Approach*, S.J. Willia G.L. Romani, L. Kaufman, and I. Modena, Eds., (Plenum, New York, 1982) pp. 17-42.

**Never Use a SQUID When
A Simpler,
Less Expensive Technology
is Adequate**

Do Use a SQUID When

- Extra Sensitivity is Required
- Nothing Else Will Meet Your Requirements
(distant noise, high fields, spatial resolution, linearity)

Magnetic Fields

Environ. fields

B (Teslas)

Earthfield



10^{-4}

10^{-5}

μT

10^{-6}

Biomagnetic fields

Urban noise



10^{-7}

10^{-8}

Car @ 50 m



10^{-9}

nT

10^{-10}

Lung particles

Screwdriver
@ 5 m



10^{-11}

Human heart

Skeletal muscles

10^{-12}

Fetal heart

Human eye

pT

10^{-13}

Human brain (α)

Transistor,
IC chip @ 2 m



10^{-14}

Human brain
(response)

Transistor die
@ 1 m



10^{-15}

fT

10^{-16}

Instrum. resolution

Flux gate
magnetometers

Optically pumped
magnetometers

SQUID
magnetometers

Car = 10^{14} pT·cm³

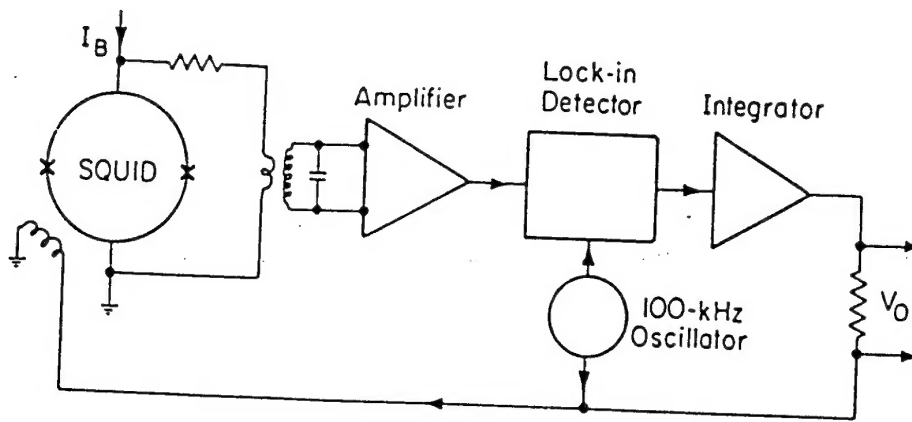
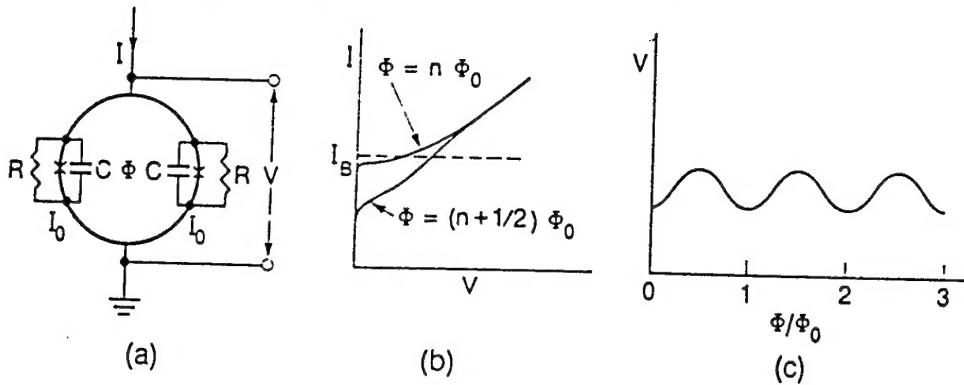
Packaged IC chip or transistor = 10^7 pT·cm³

Screwdriver = 10^{11} pT·cm³

IC chip or transistor die = 5×10^4 pT·cm³

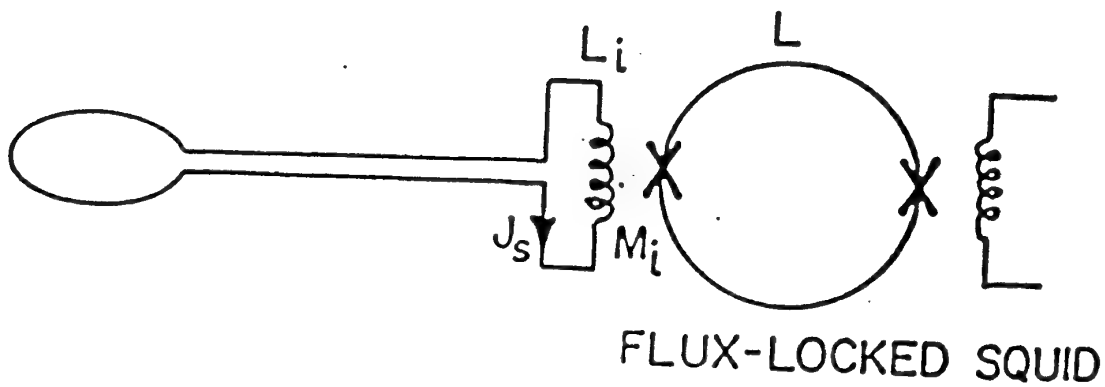
CTF SYSTEMS INC.

SQUIDS



"Principles and applications of SQUIDS," J. Clarke, *Proc. IEEE* 77: 1208-1223.

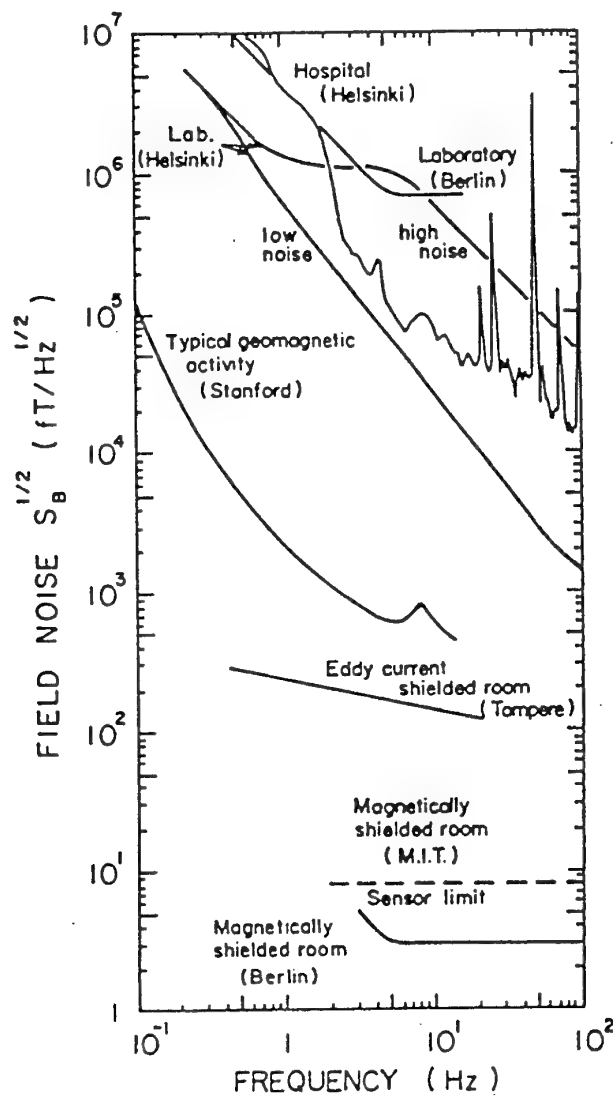
MAGNETOMETERS



- Single loop
- Multiple turns
- Field sensitivity proportional to coil area
- Sensitive to noise
- Sensitive to tilt in Earth's field

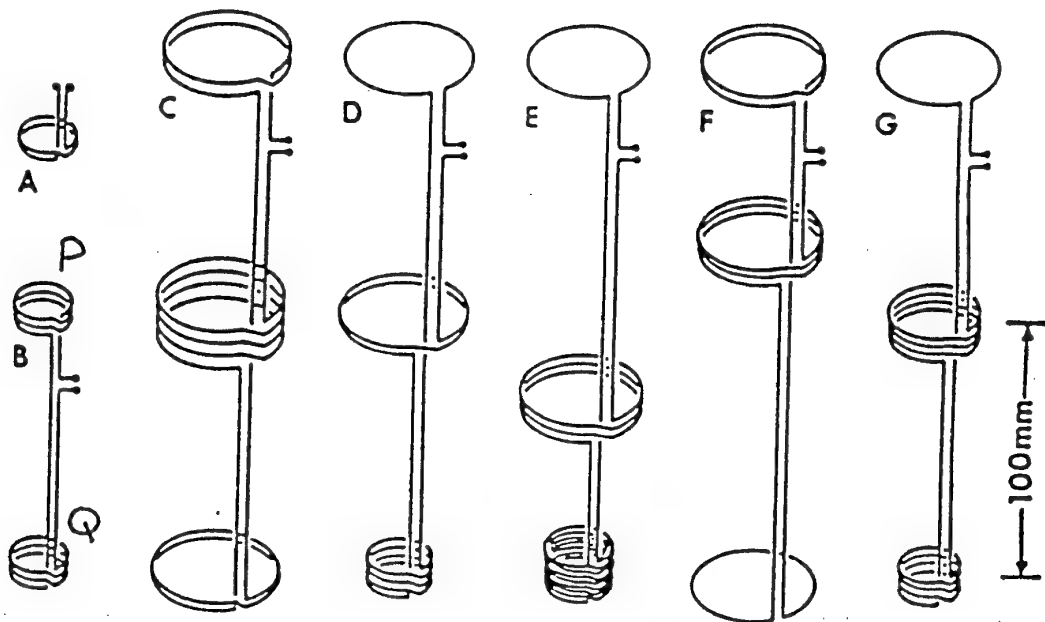
"Principles and applications of SQUIDS," J. Clarke, *Proc. IEEE* 77: 1208-1223.

ENVIRONMENTAL NOISE



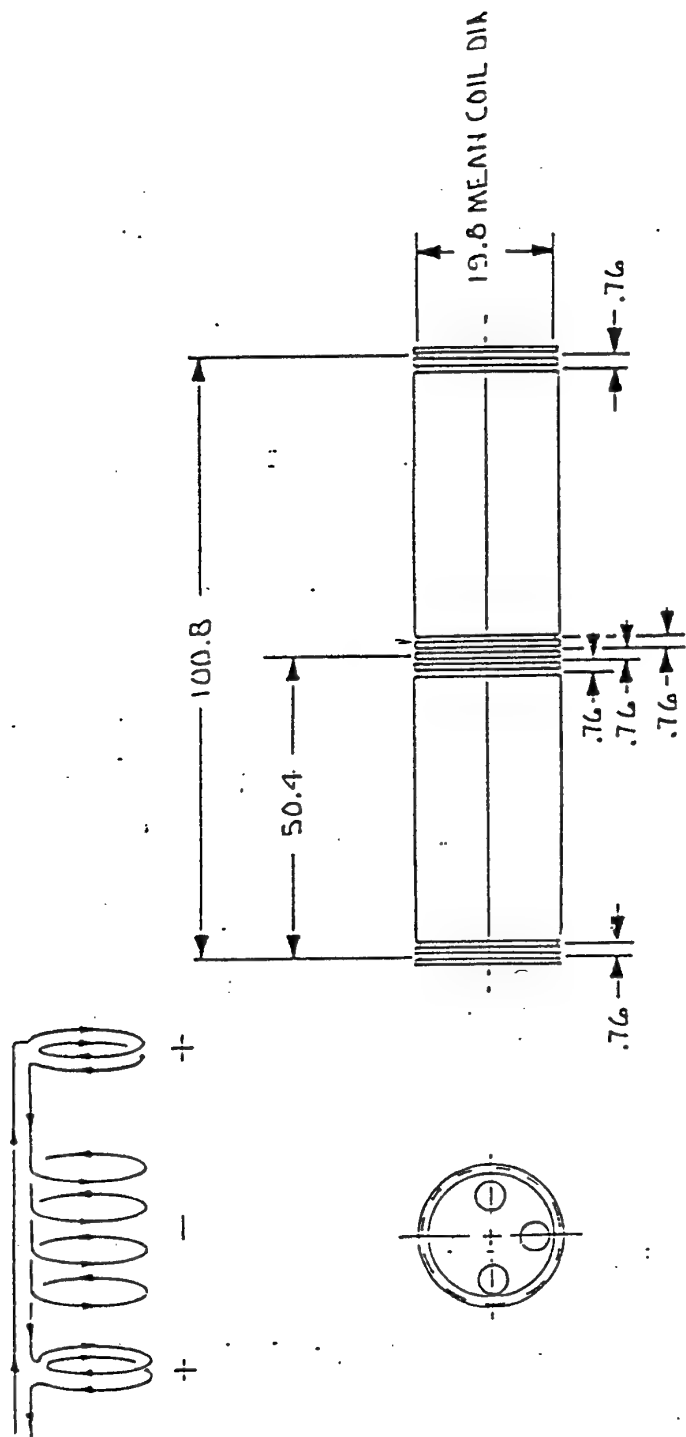
G.L. Romani, S.J. Williamson, and L. Kaufman, *Review of Sci. Instru.*, **53**: 1815 (1982)

GRADIOMETERS



- Can be balanced to 1 part in 10^7
- Insensitive to distant noise sources
- Insensitive to tilt in uniform fields
- Energy wasted in balance coils

"Optimization of SQUID Differential Magnetometers," J.P. Wikswo, Jr., *AIP Conf. Proc.*, 44: 145-149 (1978).

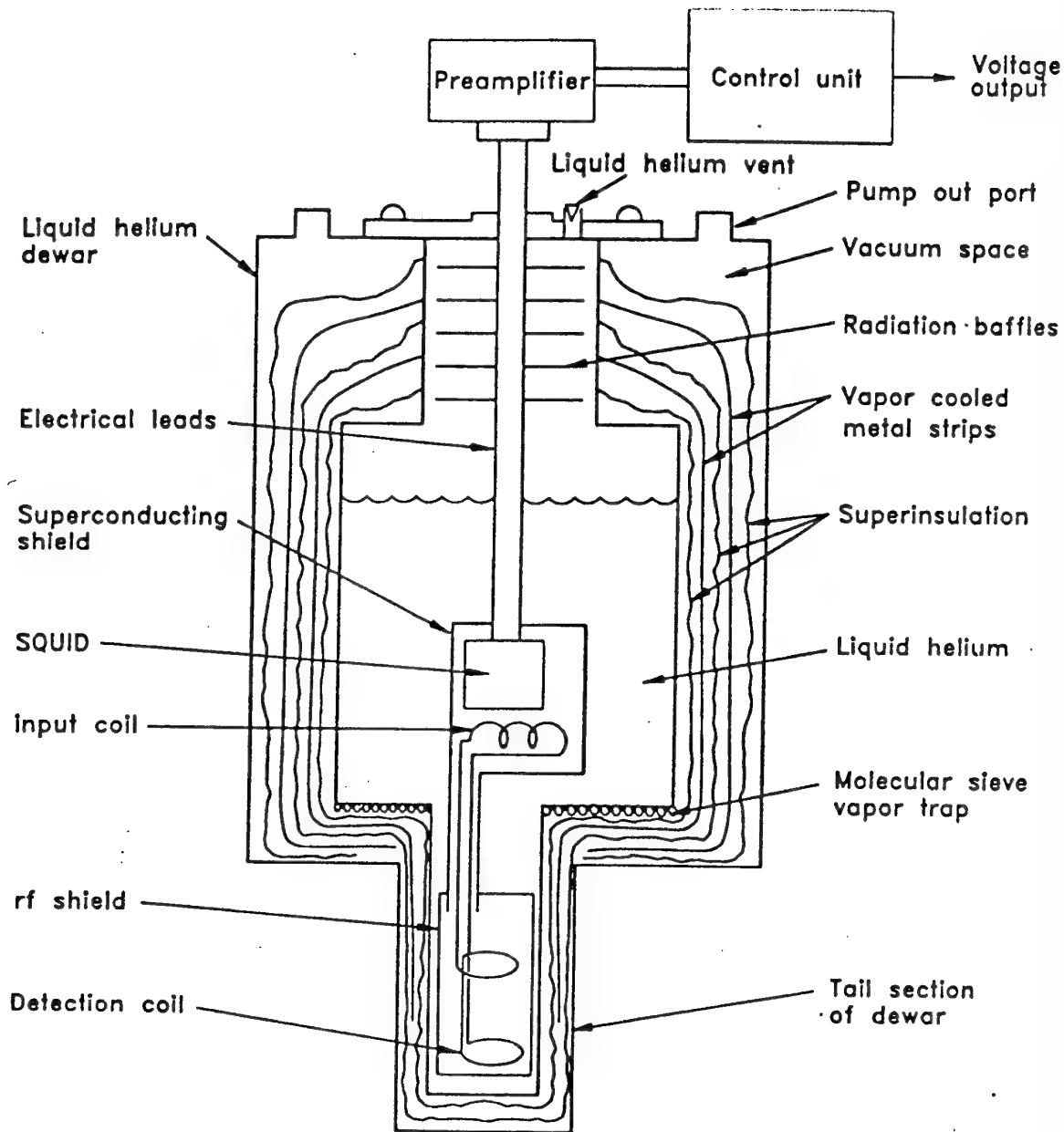


NOTES.
1. ALL DIMENSIONS ARE IN MM.

Figure 1-3. Model 601 Biomagnetometer Coil Form and Pick-Up Coil

A2001-327, Rev. C

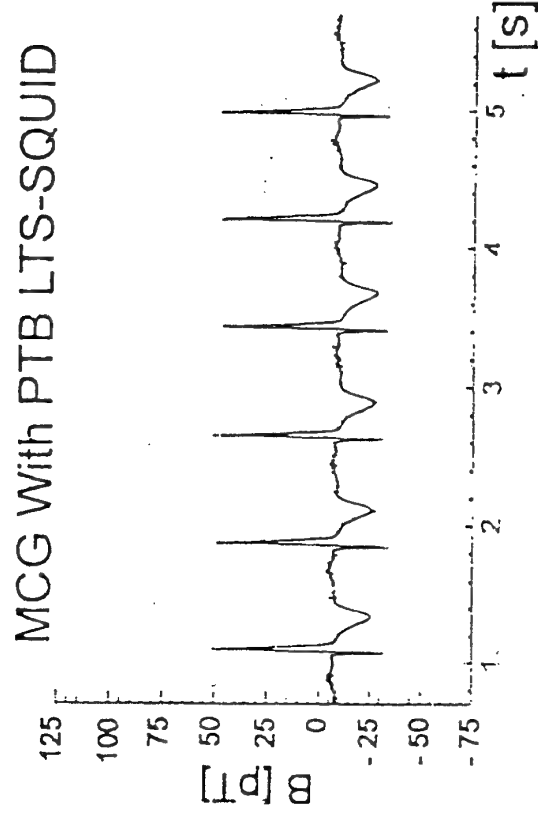
SQUID DEWAR DESIGN



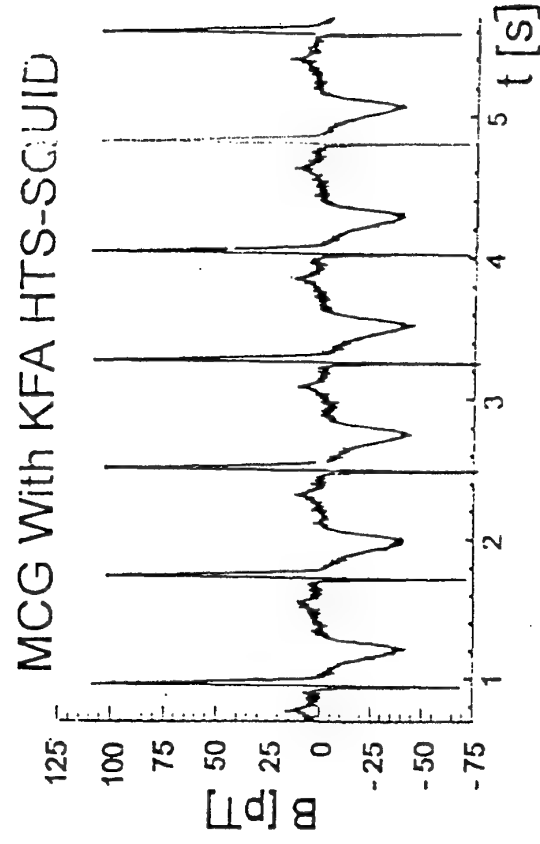
"Cryogenics," J.E. Zimmerman, in *Biomagnetism: an Interdisciplinary Approach*, S.J. Williamson, G.L. Romani, L. Kaufman, and I. Modena, Eds., (Plenum, New York, 1982) pp. 44-67.

MCG Using HTS And LTS Magnetometer SQUIDS

Inside A Shielded Room (Courtesy PTB Berlin)



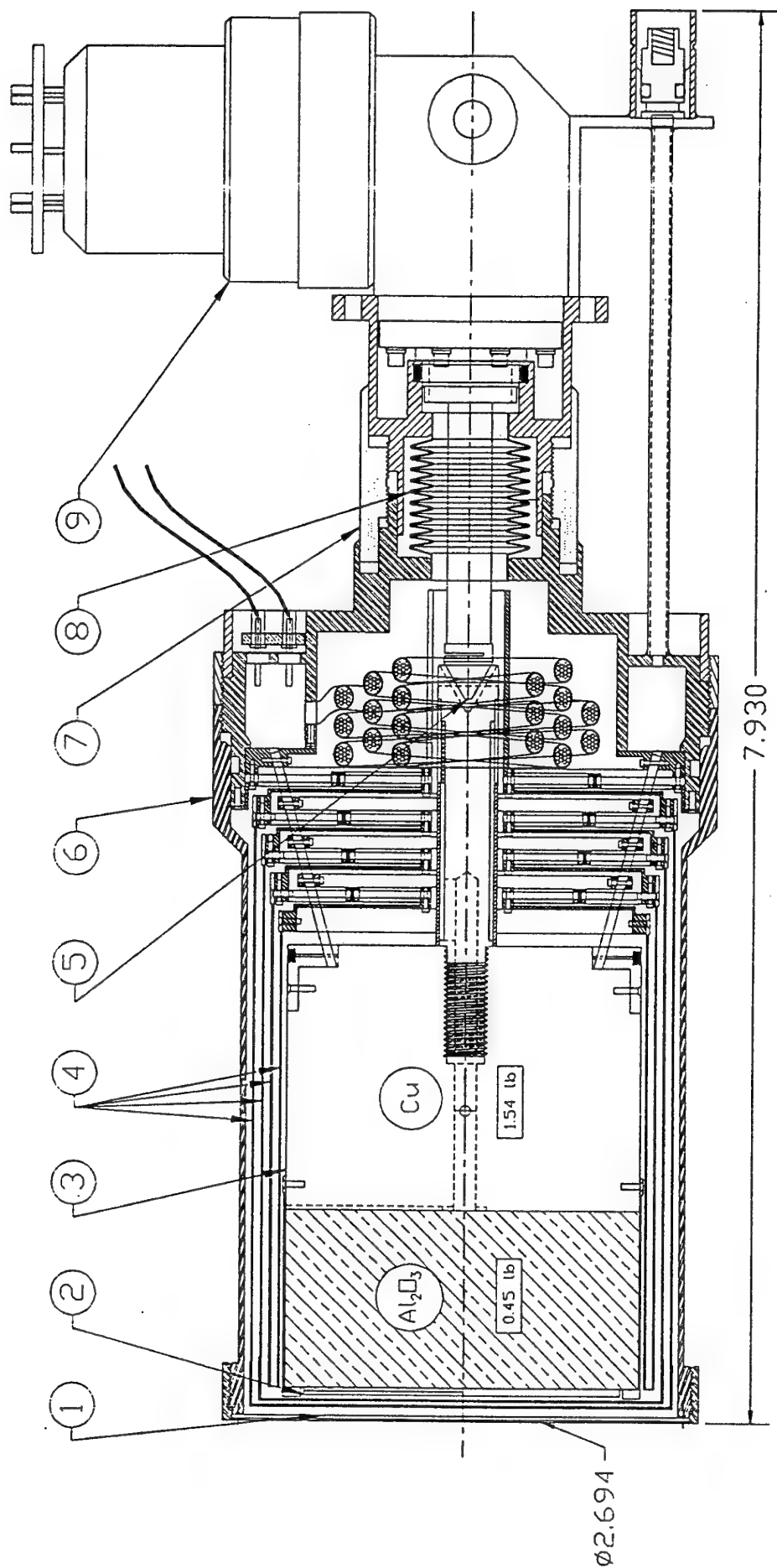
$$B_N = 25 \text{ fT}/\sqrt{\text{Hz}}$$



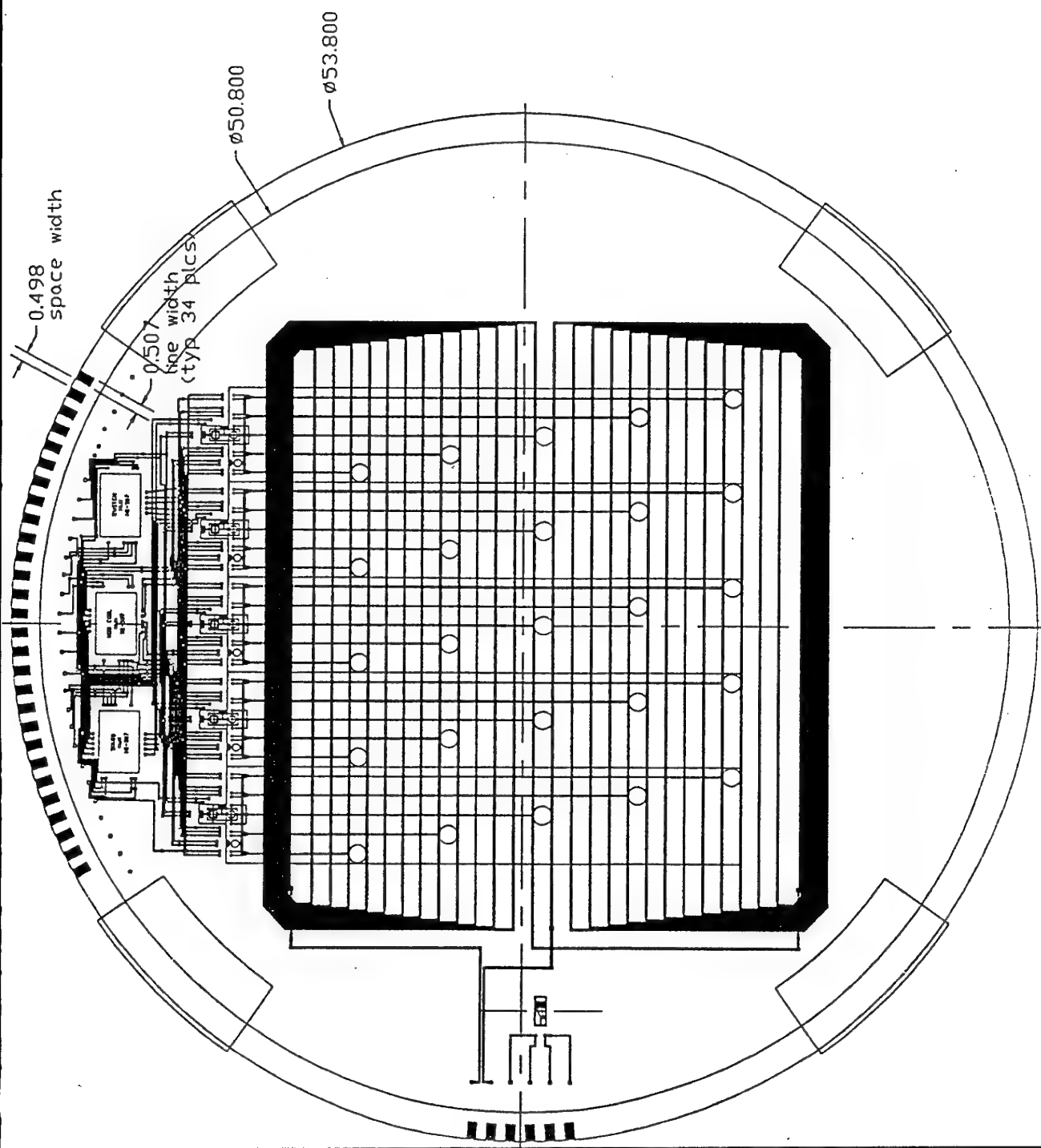
$$B_N = 40 \text{ fT}/\sqrt{\text{Hz}}$$

Video Bandwidth 250 Hz

LN₂ Makes A Smaller Source-SQUID Distance Possible!

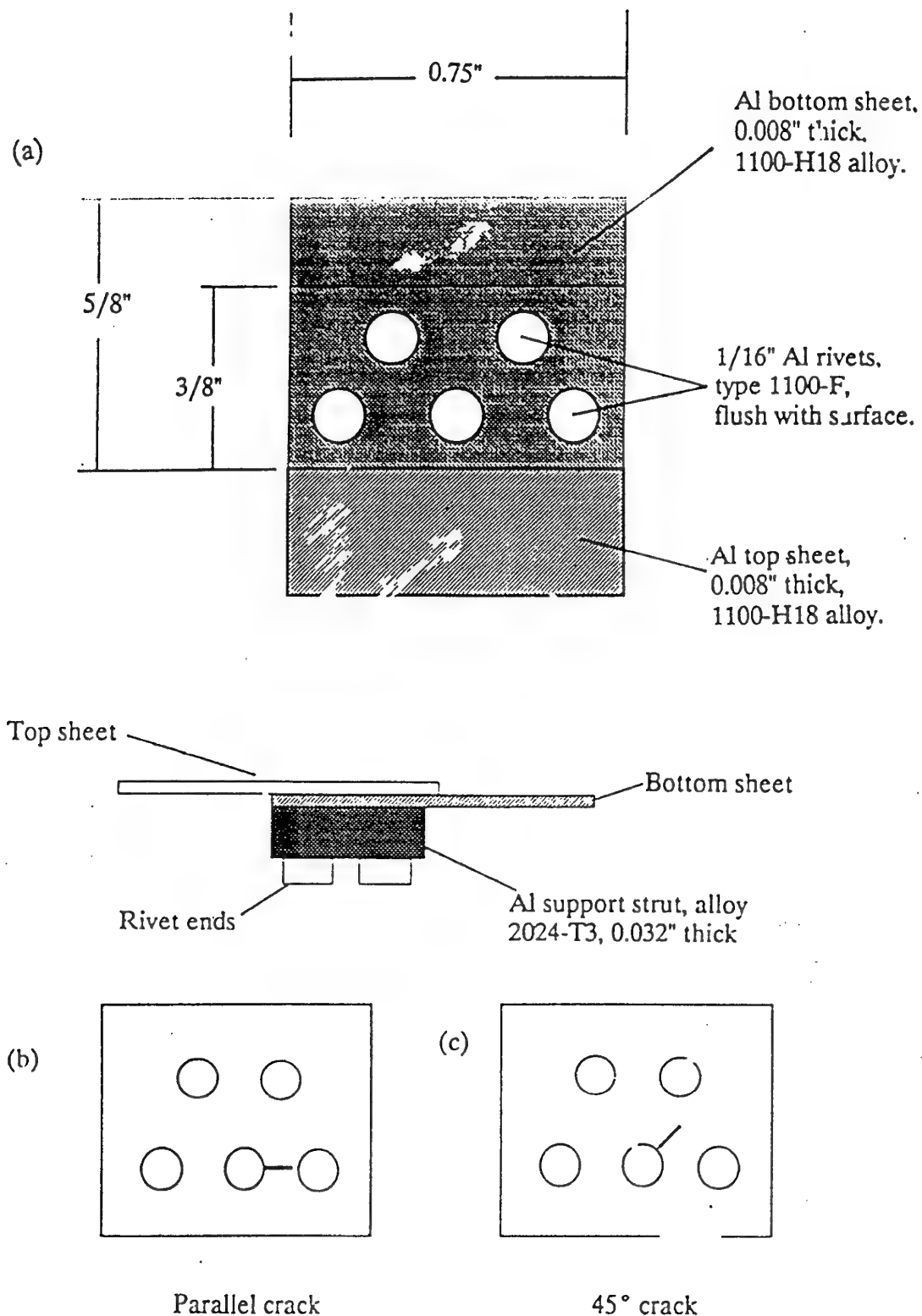


1. sapphire window	4. thermal shields	7. coupling turnbuckle
2. SQUID array	5. refrigerator cold pad	8. bellows
3. cryobattery	6. vacuum jacket	9. microcooler



*** NOTE: ALL LINEAR DIMENSIONS IN MILLIMETERS
 ALL TRACES AND JUMPERS 0.050 AG EXCEPT
 SOURCE CATH AND LEADS (0.100 YRCS)



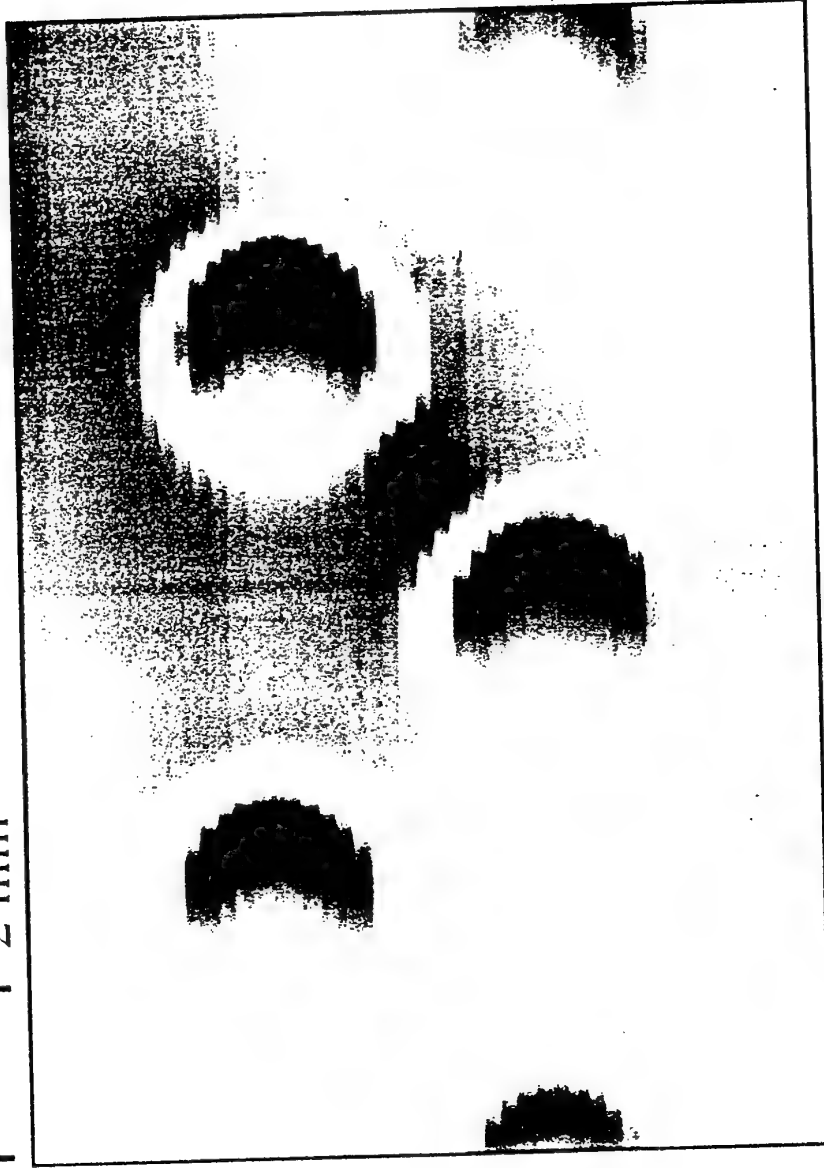


SAMPLE CONFIGURATION

Figure 3. (a) The top and side views of a model aluminum wing lap joint assembly. (b) A schematic of the lower aluminum sheet with a crack parallel to the lap joint and (c) the lower aluminum sheet with a crack at 45° to the lap joint.

$f = 30 \text{ kHz}$

2 mm



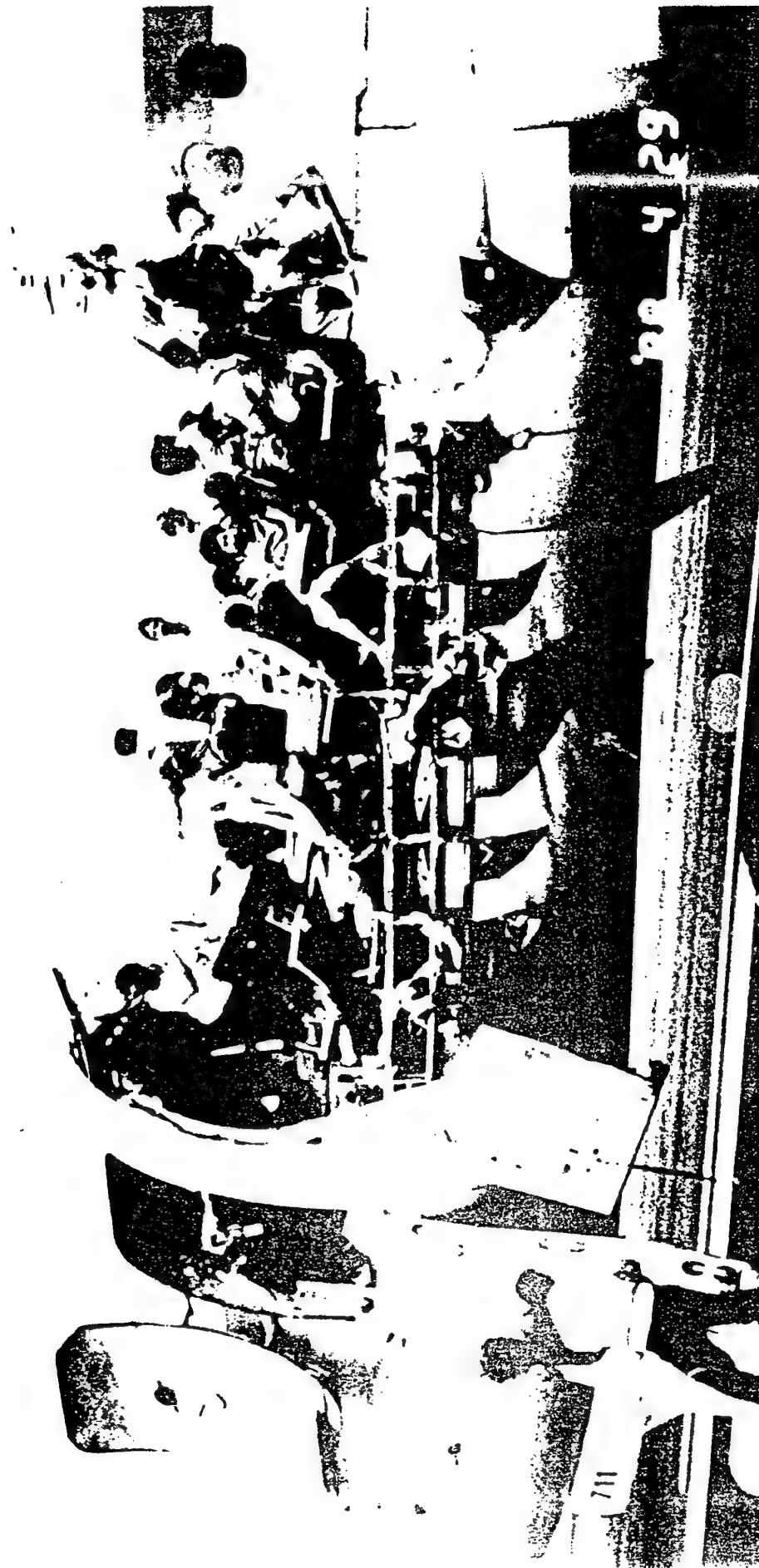
0.4



-0.8

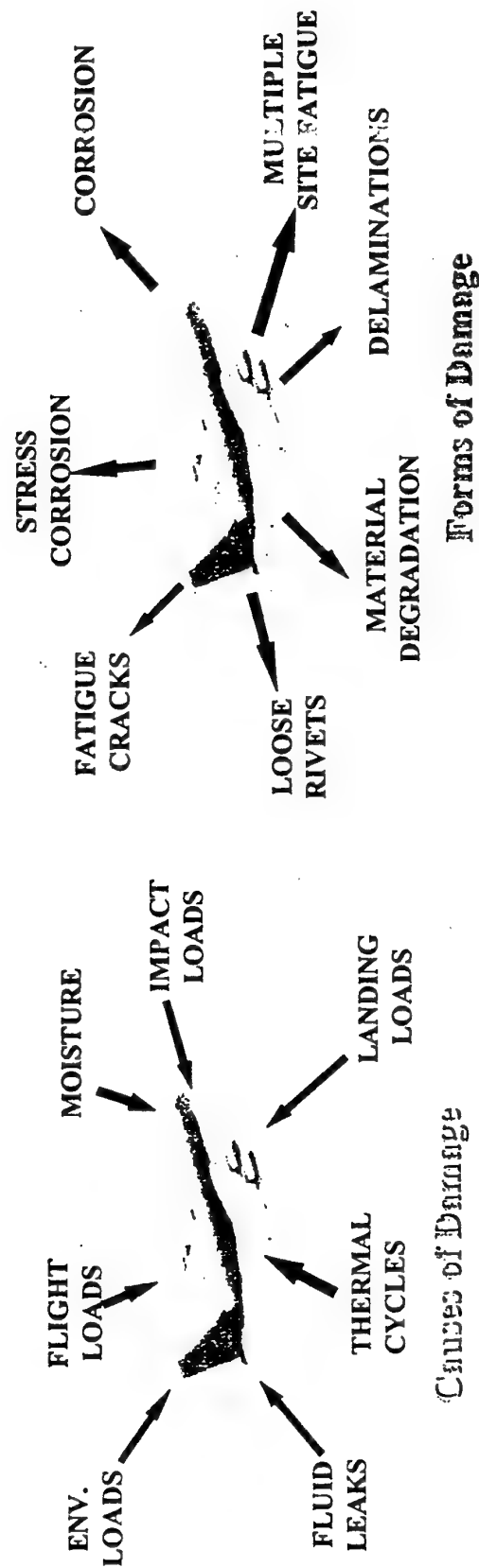
Out of Phase Response
(arbitrary units)

Figure 1. Acoustic phase response image of a 45° crack.



TECHNICAL MISSION

Perform basic research to contribute to the integrity and maintainability of aging aircraft and future aerospace systems



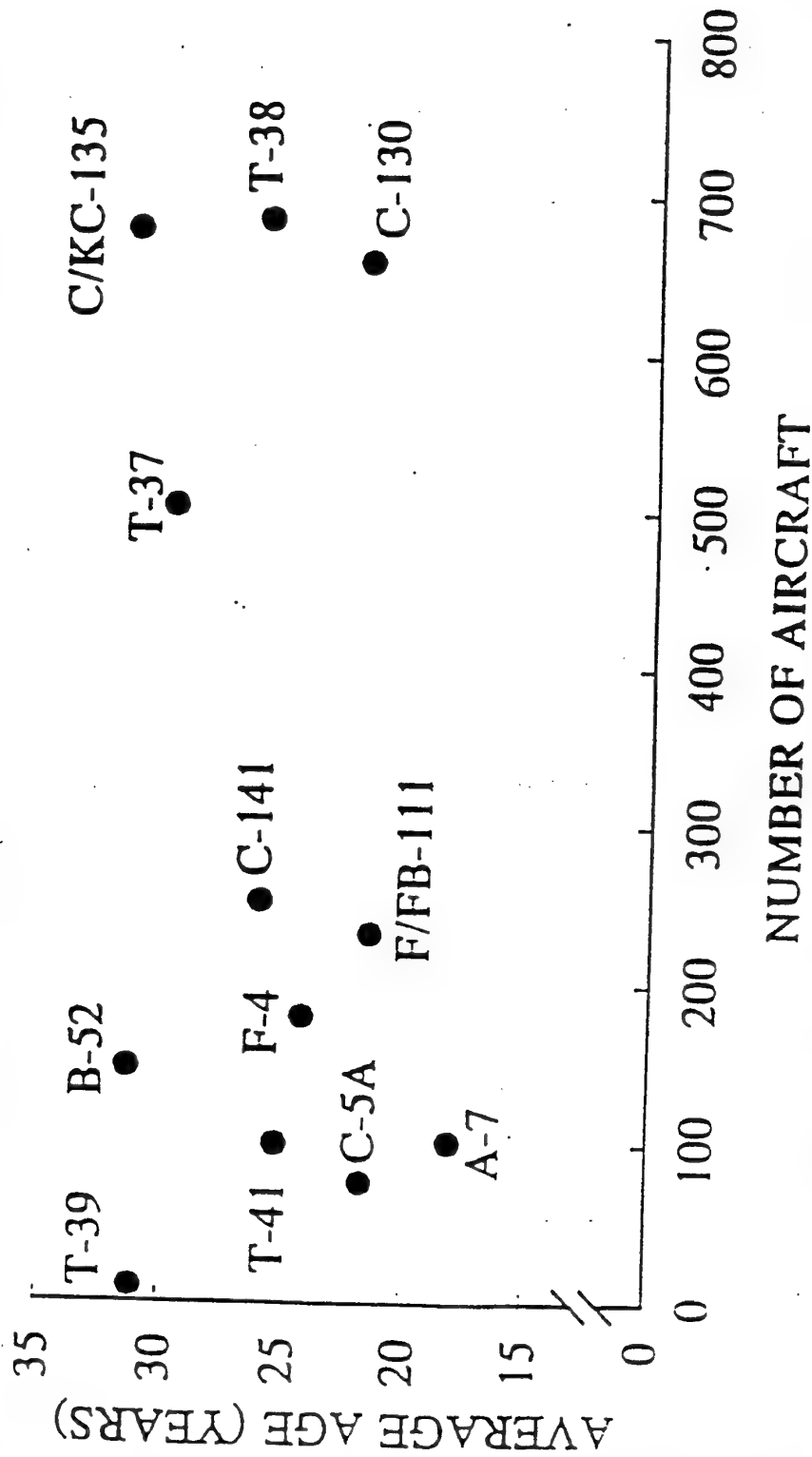
EDUCATIONAL MISSION

Produce qualified graduate and post-graduate students in fields relevant to AF needs

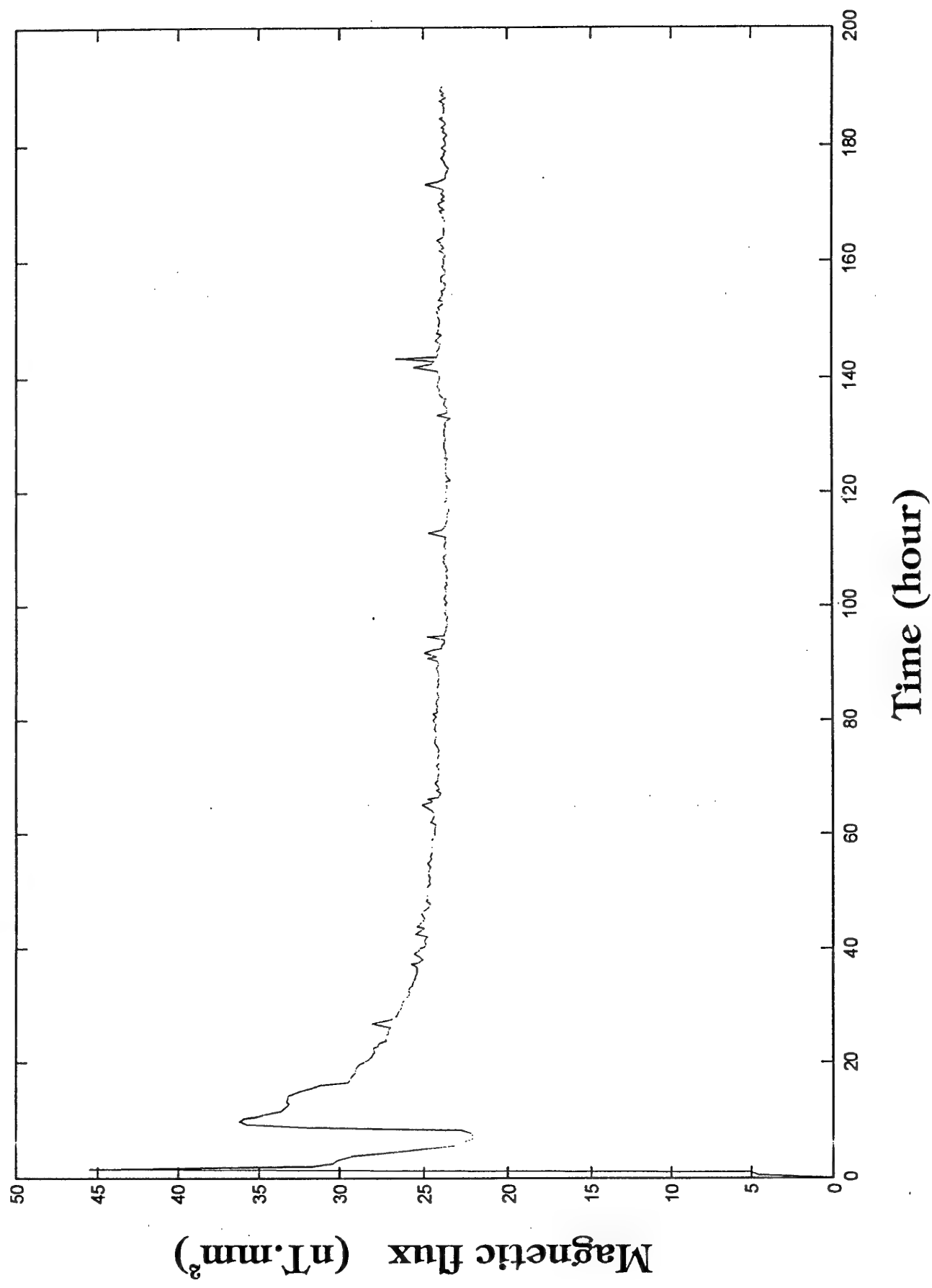


FAST

Air Force Aging Aircraft



Net magnetic flux per scan v.s. Time



Magnetic Shield

SQUID

Sample Holder

4.0

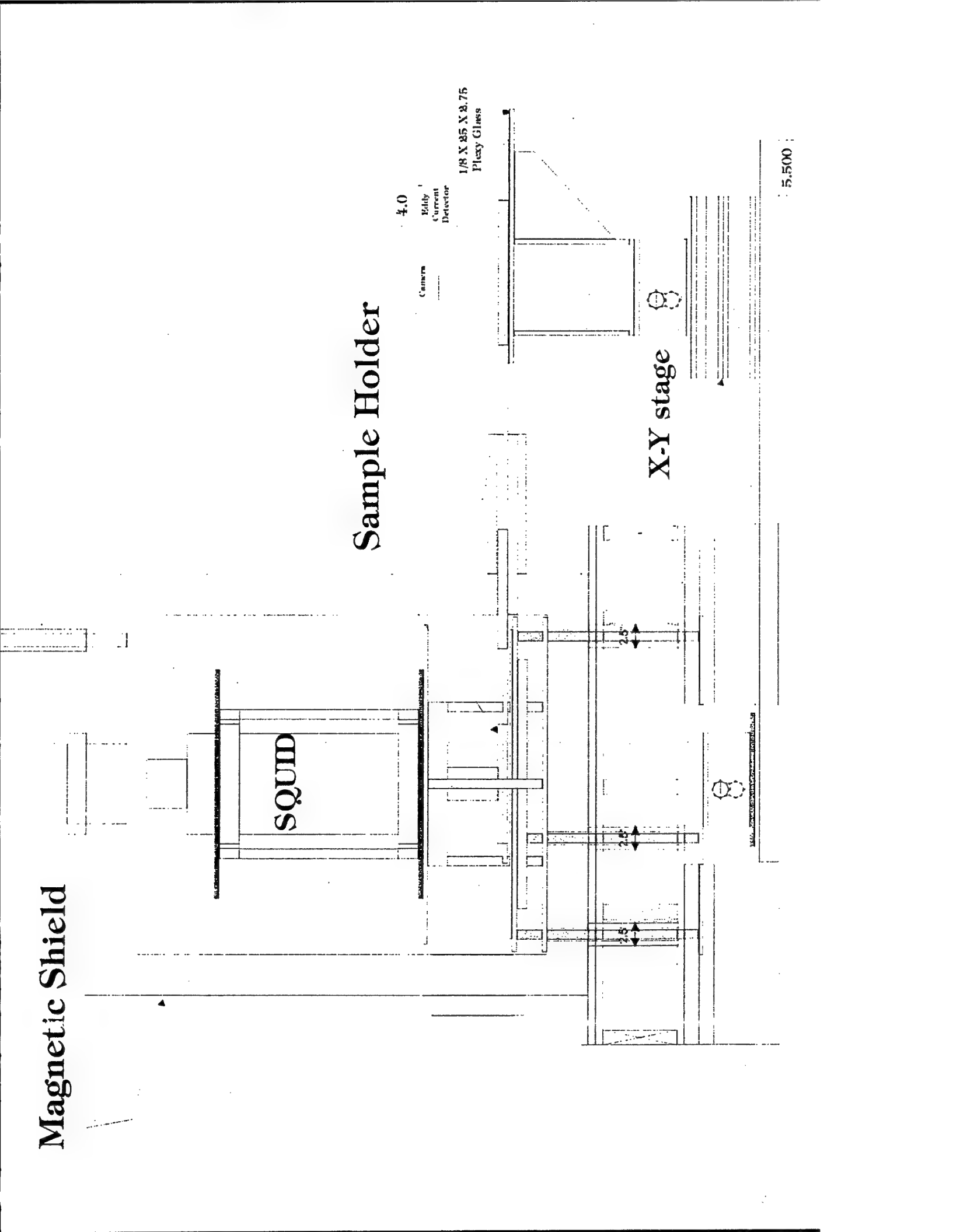
Bddy
Current
Detector

Camera

1/8 X 25 X 2.75
Plexy Glass

X-Y stage

5.500



INSPECTION TECHNIQUES

VISUAL (80%)

PENETRANT

HIGH FREQUENCY
EDDY CURRENT

LOW FREQUENCY
EDDY CURRENT

SONIC

ULTRASONIC

X-RAY RADIOGRAPHY

NEUTRON RADIOGRAPHY

MAGNETIC PARTICLE
METHODS

LASER-BASED OPTICAL
METHODS

X-RAY DIFFRACTION

THERMAL WAVE IMAGING

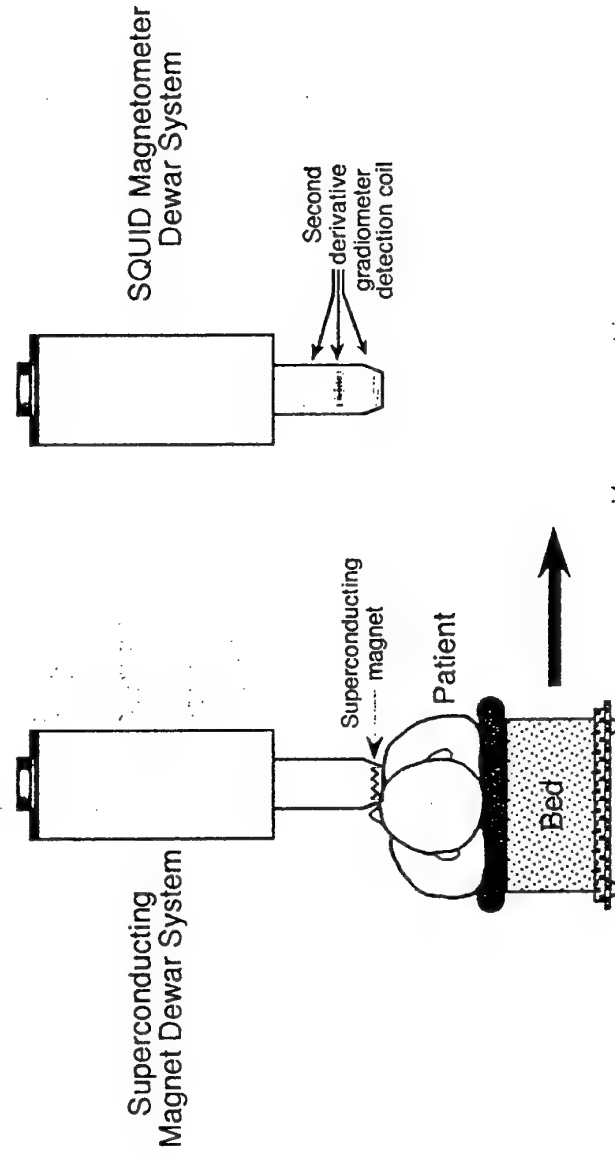
ACOUSTIC EMISSION

POTENTIAL DROP METHODS

Magnetopneumography

- Body is normally diamagnetic or paramagnetic
no naturally occurring ferro- or ferrimagnetic constituents
- Ferrimagnetic materials associated with particulate contaminants
dust in lungs of coal miners, welders, asbestos workers
magnetite dust tracer for lung clearance studies
- Allows lung clearance studies
 $M = m_s (1 - e^{-3H/Q})$
70 mT (5 sec) \Rightarrow 90% saturation of ferrimagnetic particles
 $M_H = \text{constant} = m_s (1 - e^{-t/\tau_H})$
 $\tau_{\text{ferrimagnetism}}$ as short as minutes
- Example of Research, not Clinical Application

Magnetopneumography Measurement Techniques



- Magnetize lung
 $H \sim 100 \text{ mT}$ 9 cm below magnet
- Move subject beneath magnetometer
- Scan magnetometer for remnant magnetism
500 picogram/cc sensitivity $\approx 1 \mu\text{gram}$ total particulates
 $\Delta t \geq 10$ seconds

Mesenteric Ischemia

- Mesenteric arteries carry blood to the stomach, small and large intestine
- Blockage of the blood flow (ischemia) can lead to intestinal necrosis
- Symptoms are primarily abdominal pain, usually 30-90 minutes after eating
often ignored
- Diagnosis of mesenteric artery narrowing or blockage is by arteriogram
requires catheter and X-ray dye
limit on size of vessels that can be seen by X-ray
- Treatment requires surgical intervention
 - if intestinal tissue is necrotic, segment(s) must be removed or bypassed
 - if diagnosis delayed, mortality rate can exceed 50%

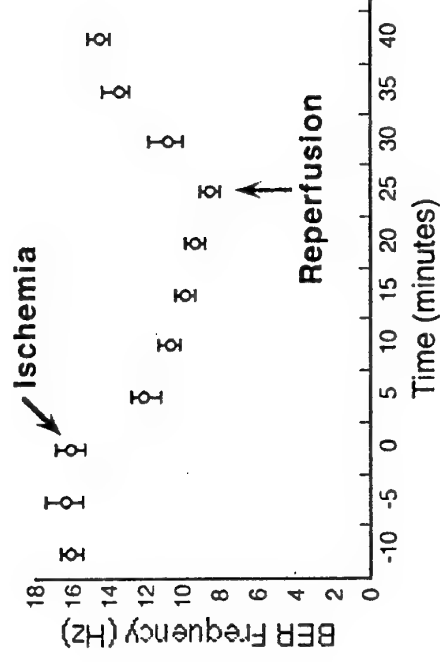
Basic Electric Rhythm

- Gastrointestinal (GI) tract exhibits two types of electrical activity
high frequency spiking associated with muscle contraction

Low frequency oscillations known as electric activity or basic electric rhythm (BER)

Human gastric BER	$\approx 3.2 \pm 0.1 \text{ Hz}$
Small intestine BER	$\approx 11.3 \pm 0.1 \text{ Hz}$
duodenum BER	$\approx 12 \text{ Hz}$
terminal ileum BER	$\approx 8 \text{ Hz}$

Ischemic Episodes Show Marked Reduction in BER

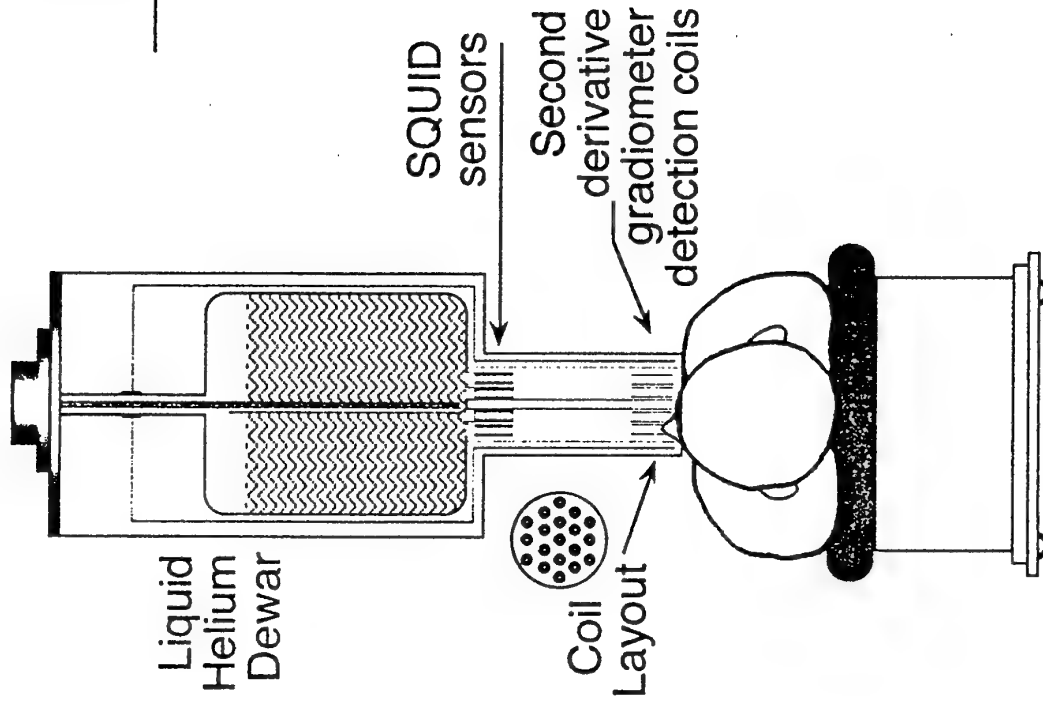


BER frequency before and after occlusion of mesenteric artery

Statistically significant frequency shift may permit diagnosis

Instrumentation for Ischemia

- Subcutaneous electrodes ~ mV
Highly invasive
not a clinical procedure
- SQUID Magnetometer ~ pT
Not invasive
- Status
First 3-channel system at Vanderbilt
Building 19 channel system for preclinical studies
has vector (B_x , B_y , B_z) channels
- Example of a Pre-Clinical Application



Biomagnetic Liver Susceptometry

- Medical Motivation
- Iron in the Human Body
- The Differential Measurement
- Calculation of Iron Concentration (χ)
- Magnetic Detection First Shown in Animals
- The SQUID Magnetometer
- The Instrument
- Measurement Protocol
- Clinical Validation of Magnetic Measurement
- Conclusions

Medical Motivation

Genetic diseases, which directly or indirectly cause iron overload

Disease:	Hæmochromatosis	Thalassemia	Sickle-Cell Anemia
Symptoms:	none in early stages; diabetes, arthritis, myocardial infarction, cirrhosis, etc. in later stages, anemia, tiredness	anemia, tiredness	anemia, hypoxemia

Source of excess iron: abnormal absorption from diet transfusion, some excess absorption whole blood transfusion

Therapy for Iron Removal: phlebotomy chelation chelation

Other Therapy: spleenectomy, bone marrow transplantation equal exchange transfusions

Incidence*: (U.S. figures) 0.25% - 0.5 % affected ~10% have trait 1.5% 0.3% blacks affected, 7% have trait

Main Sub population affected Northern European decent Mediterranean decent African or Hispanic decent

Consequences: Long-term exposure to high levels of iron in the body cause diabetes, growth disturbances, arthritis, and irreversible damage to endocrine glands, heart and liver.

Iron in the Human Body

~ 4 Grams of Iron in Healthy Adult

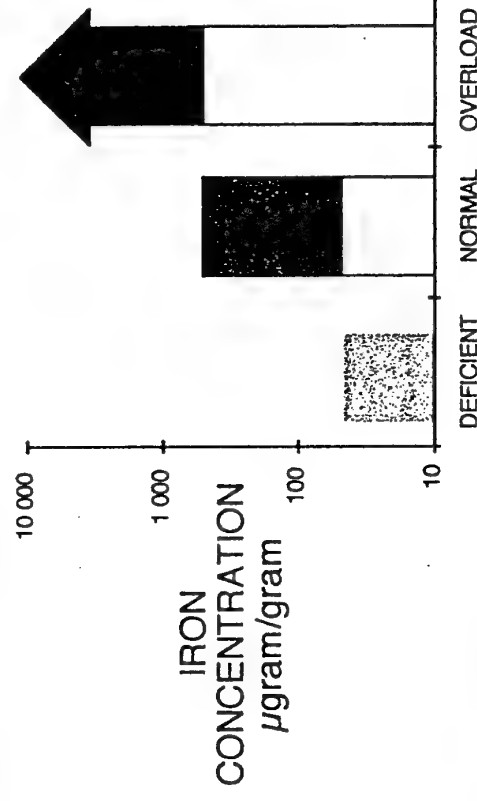
~ 3 grams involved in biochemistry, primarily oxygen transport

~ 1 gram of iron is stored in specialized protein molecules (e.g., ferritin, hemosiderin).

The major storage location is the Liver

Secondary storage locations are the Spleen and, when overloaded, the Heart

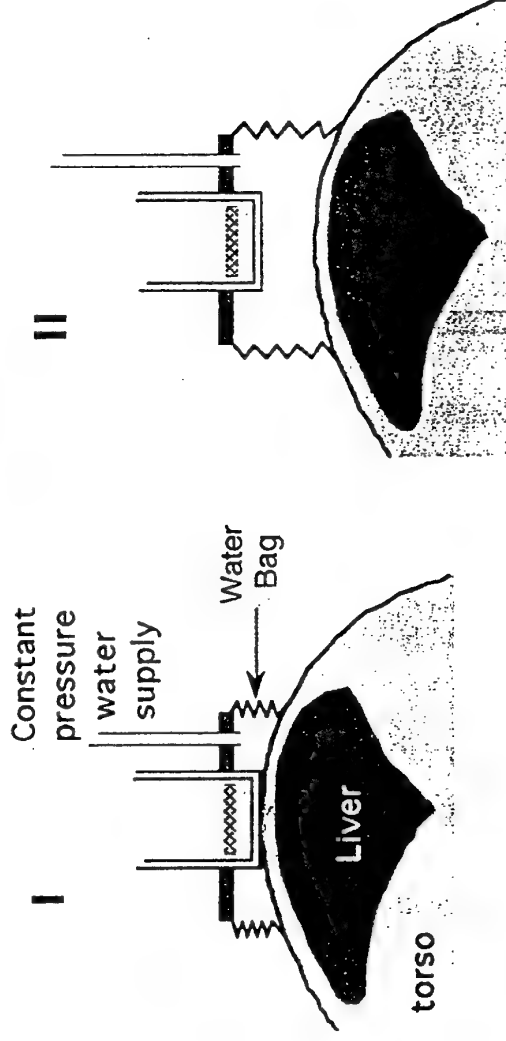
When greatly overloaded, as much as 50 gram of Iron stored in 1.5 kg liver



The iron stored in the ferritin molecule is paramagnetic

The concentration of iron can be determined by a magnetic susceptibility measurement $\chi = B/H$

The Differential Measurement



- Susceptibility of Liver sum of iron ($\propto [\text{Fe}]$) and liver tissue
- The Liver is surrounded by tissue
 - χ_{liver} is non-zero
 - $\chi_{\text{liver}} \approx \chi_{\text{water}}$
- Use of Water Bag simulates uniform medium
 - Measurement is made by lowering the subject (I)
 - Water effectively replaces the torso by water (II)

Calculation of Iron Concentration (χ)

First Order

$$\chi_{liver} \ll \chi_{tissue} \text{ (skin, fat, muscle, ribs,...)}$$

$$V(z) = C \Delta\chi_{liver} \Phi + \Delta V_{system}(z) + V_O(z)$$

$$\Phi(z) = \int H_{magnet} \cdot B_{coils} dr^3$$

Second Order

$$\chi_{liver} \leq \chi_{tissue}/10$$

$$V(z) = C \{ \Delta\chi_{tissue} \Phi_{tissue} + \Delta\chi_{liver} \Phi_{liver}(z + z_{liver}) \} + \Delta V_{system}(z) + V_O(z) + O_3$$

By fitting output voltage as a function of depth, χ can be determined

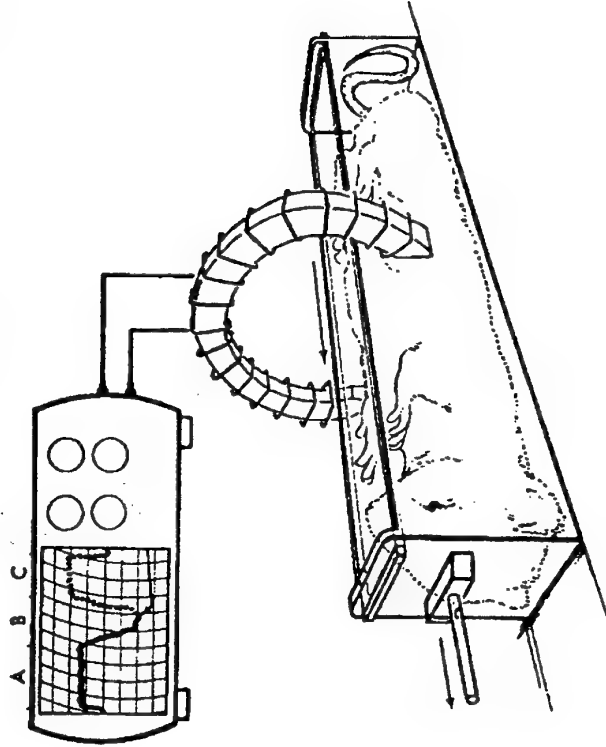


Tristan
Technologies

Magnetic Detection First Shown in Animals

"Estimation of Hepatic Iron Stores by In-Vivo Measurement of Magnetic Susceptibility"

John H. Bauman and John W. Harris, *The Journal of Laboratory and Clinical Medicine*, 70, 246 - 257 (1967)



Control Rat Iron-Loaded Rat



Live, Intact Rats

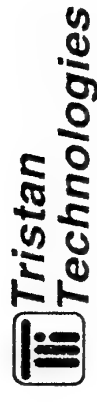
The SQUID Magnetometer

- Amplifier is Superconducting QUantum Interference Device (SQUID)
 - Operates at cryogenic temperatures
- Measures Magnetic Fields better than anything else
 - Sensitivity as low as femtoTesla
- Highly Stable and Repeatable in large magnetic fields
 - better than parts per million/hour in Tesla fields
- Very Reliable
 - Fundamental technology commercially available since 1970
 - 12 year operational history as measurement of iron stores
- Sites in Hamburg, Germany and New York
 - Systems under construction for Torino, Italy and California

Clinical Biomagnetism

- Advantages of Biomagnetism
- Magnetopneumography
- Biomagnetic Liver Susceptometry
- Intestinal Ischemia
- Issues in Clinical Applications

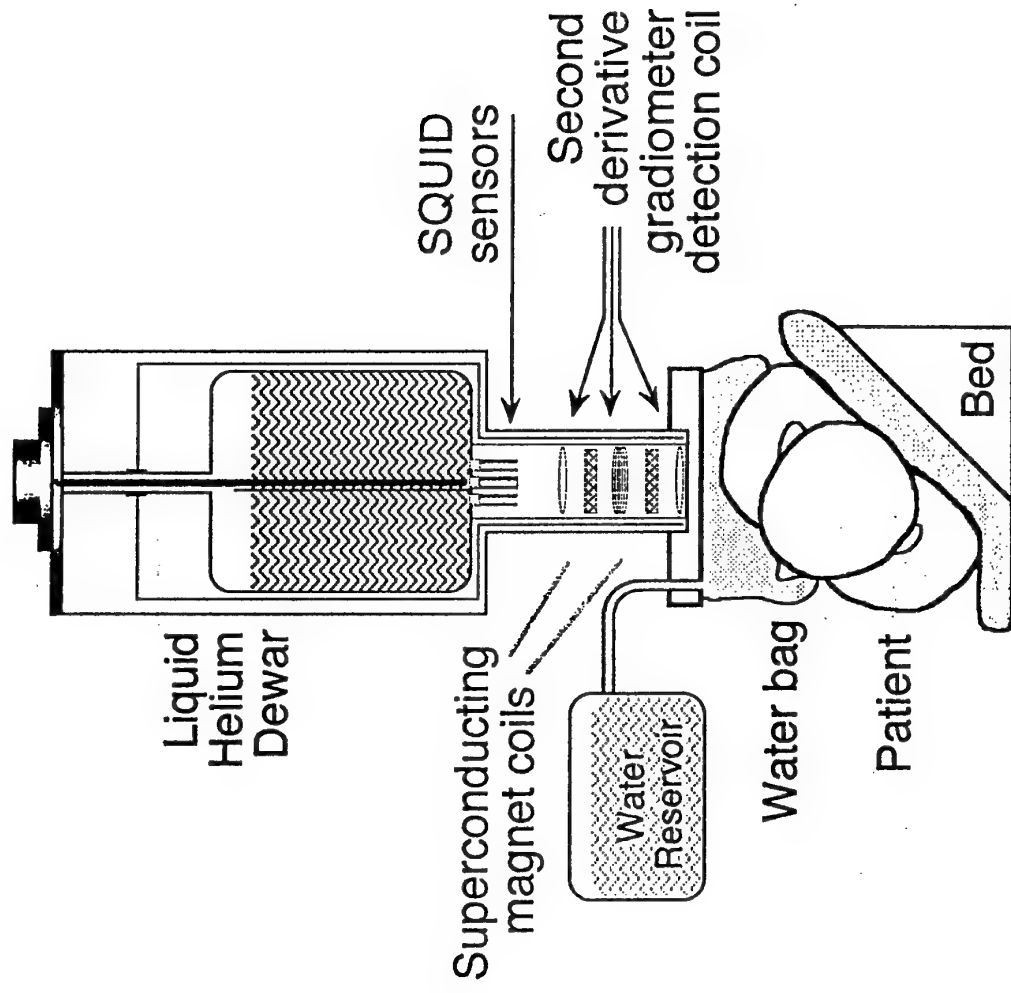
Robert L Fagaly
Tristan Technologies,
San Diego, USA



Introduction

- Useful in identifying electrophysiological activity
- Biomagnetism has significant advantages over electrical recordings
 - Non-Invasive
 - e.g.*, Intestinal Ischemia
 - Measures a vector quantity—magnetic field, rather than a scalar quantity—voltage
- Many magnetic analogs to electrical activity
 - MCG (Baule & McFee)
 - MEG (Cohen)
- There are also biomagnetic signals that have no electrical analogs.
 - Biomagnetic Liver Susceptometry
 - Magnetopneumography

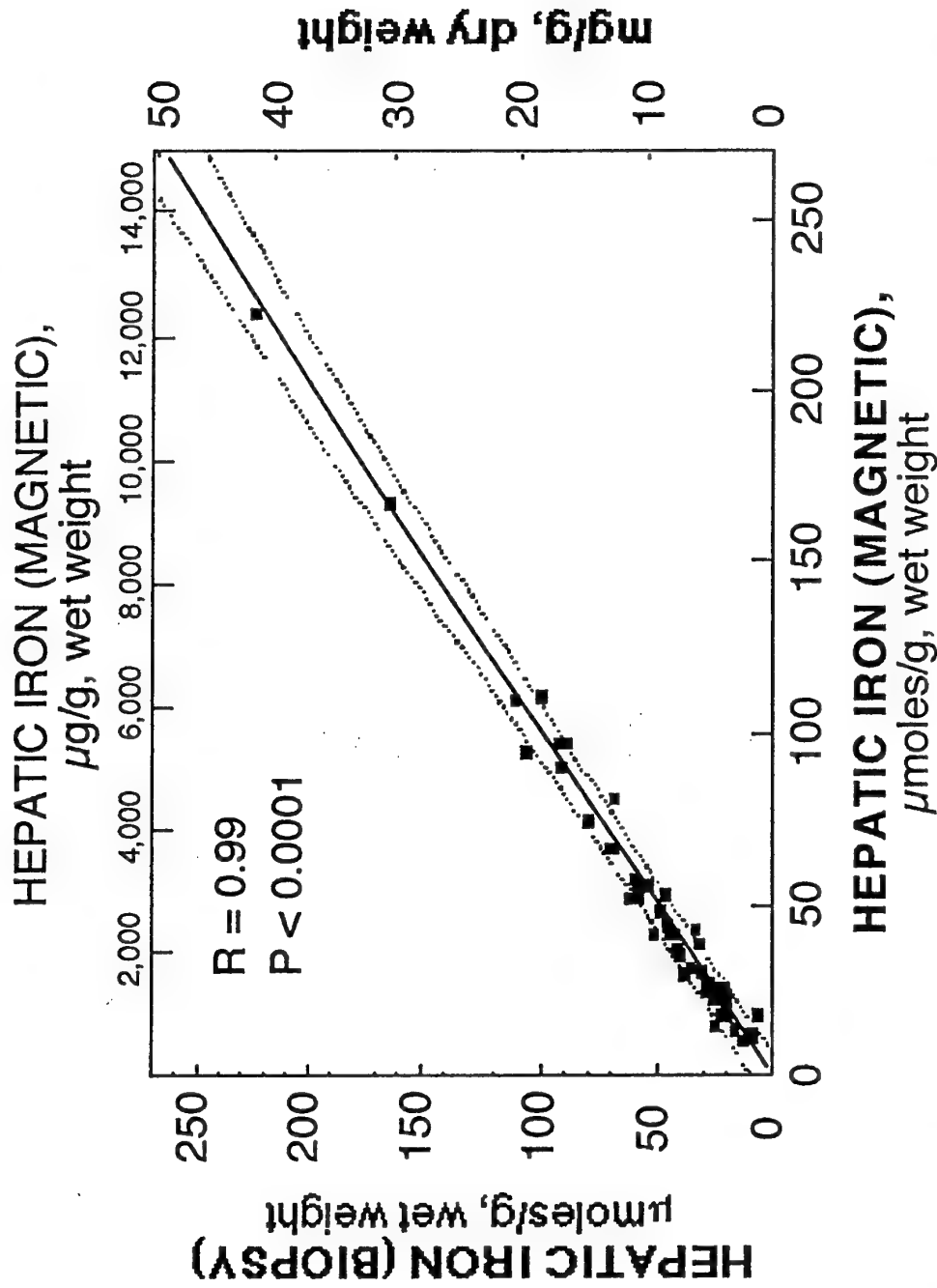
The Instrument



Measurement Protocol

- Ultrasound Measurements
- Patient Positioned Beneath Detection Coils
- Patient Raised to Bottom of Dewar Tail - Water Bag Filled
- Patient Lowered - Water Bag Filling
- SQUID Electronics Yield Voltage Change
- Calculation of Hepatic Iron Concentration (χ)
- Patient Report

G. M. Brittenham *et al*, "Magnetic-Susceptibility of Human Iron Stores", *New England Journal of Medicine* 307 1671 (1982)



Comparison of hepatic iron concentration as determined by magnetic susceptibility and by chemical analysis of liver tissue obtained by clinically indicated biopsy. Magnetic and biochemical measurements were made within 1 month; patients with cirrhosis or with biopsy specimens less than 5 mg, wet weight, were excluded..



Tristan
Technologies

Conclusions

- The magnetic biopsy gives accurate assessment of iron stores
 - Direct measurement of iron
 - Repeatability better than 5%
- Non-invasive!
 - Allows serial measurements
 - Allows pediatric measurements
- Rapid Results
 - Measurement time (including ultrasound) < 30 minutes
- Proven Technique
 - >2,100 Patients measured
- Commercially available

Issues That Must Be Solved For Any Biomagnetic Measurement System to Gain Market Acceptance

- Must be a *Clinically Accepted Method* (efficacy)
- Must offer *significant* improvement over conventional methods or,
- Must offer new information not achievable by conventional methods
- Must be cost effective
 - either address a large patient population
 - Cost not the sole decision driver
 - or, if addressing an orphan disease
 - Cost becomes significant
- Must be “easy” to use
 - staffing requirements can significantly effect acceptability
 - need to minimize visibility of cryogens
- Third Party Reimbursement important
 - see above

Commercialization of SQUIDS

- The Basic Instrument
- Applications
- Product Costs
- Market Sizes
- History
- Commercial Companies
- Obstacles
- Conclusions

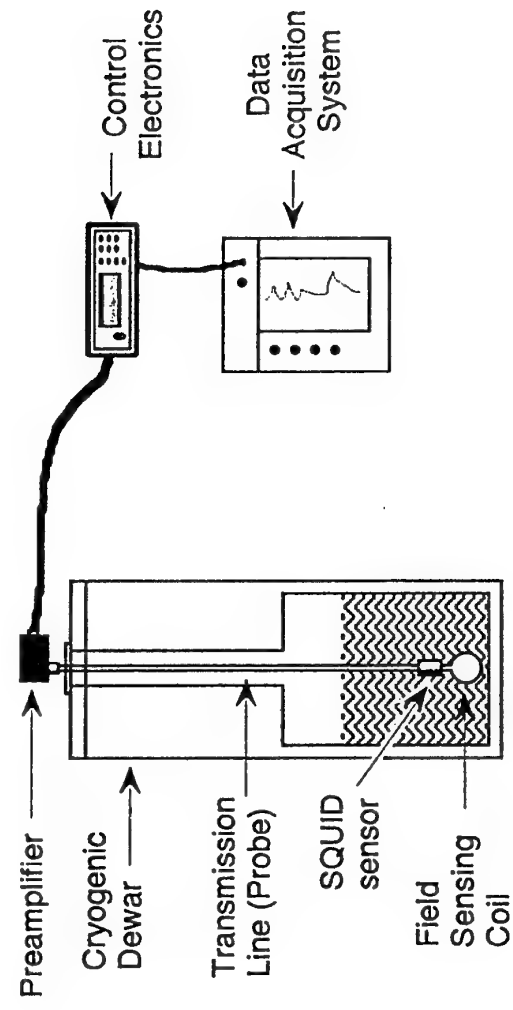
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Tristan Technologies,
San Diego, USA



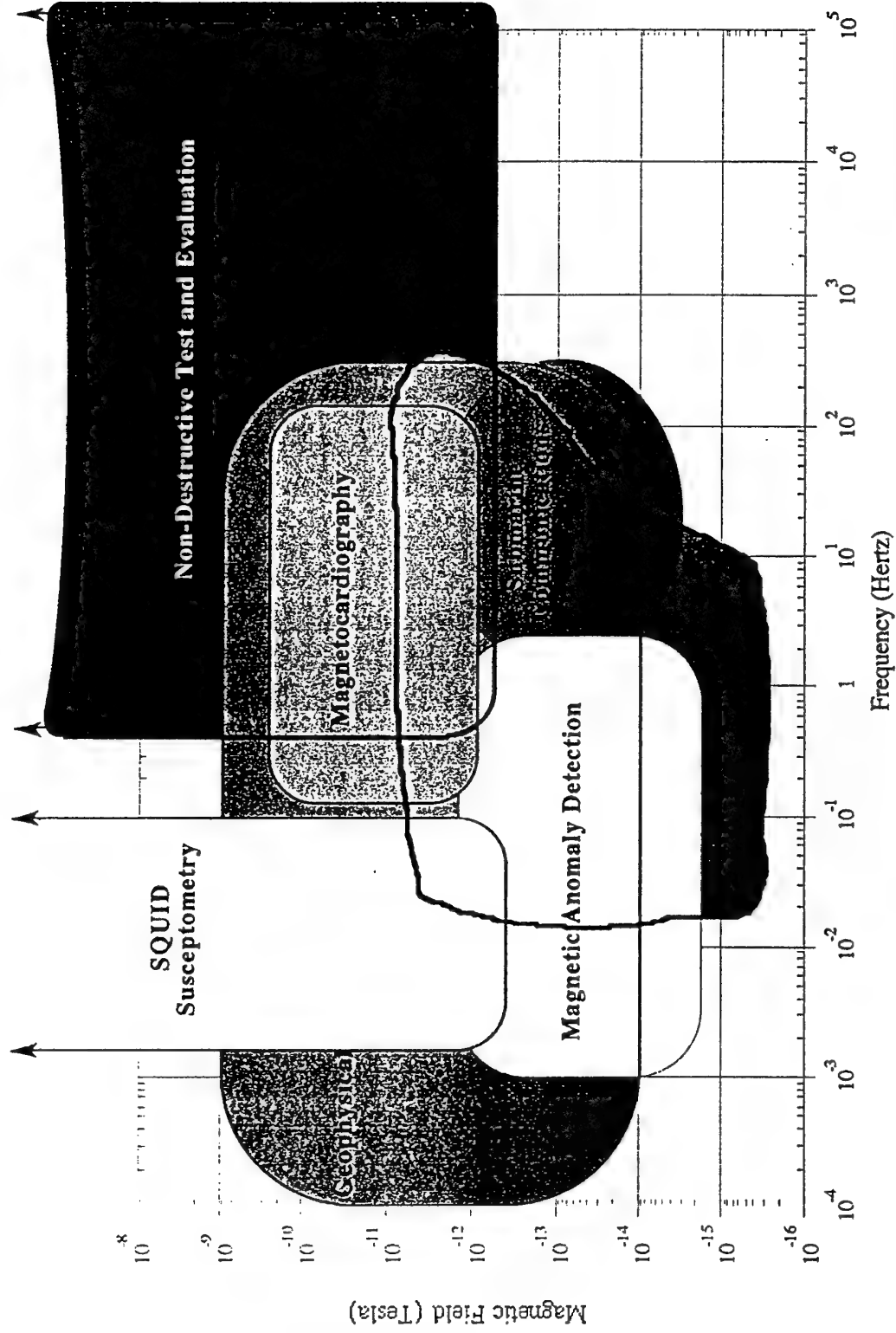
Why SQUIDS?

- It is the **most** sensitive amplifier known
- True dc response
- GHz bandwidth
- Zero phase distortion
- Noise levels below 10^{-31} J/Hz
- High dynamic range: >180 dB
- Excellent linearity: 1:10⁷
- Physically compact

The Basic Instrument

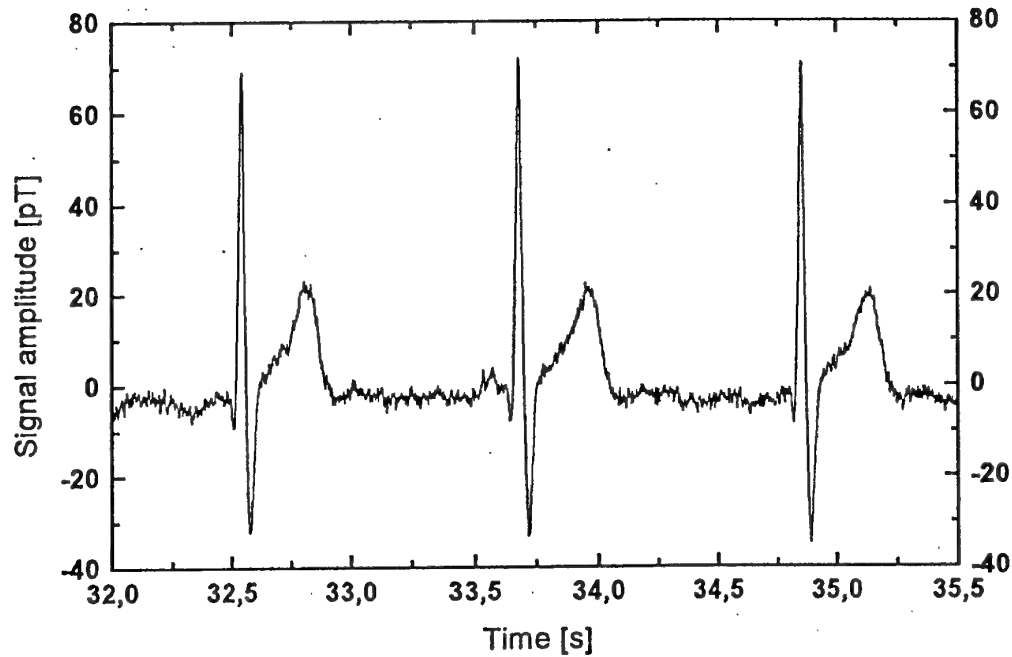


What Can I Do With It?





HTS DC-SQUID flip-chip magnetometers



An example of a real-time MCG-measurement with the flip-chip magnetometer.

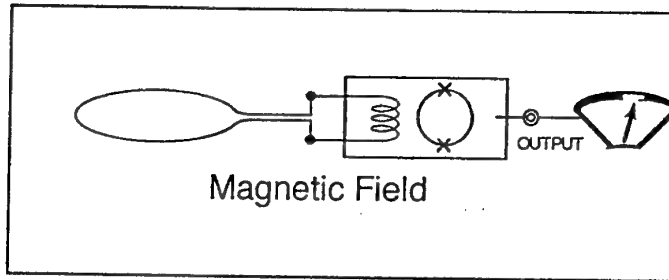


Sensor head for a DC-SQUID microscope

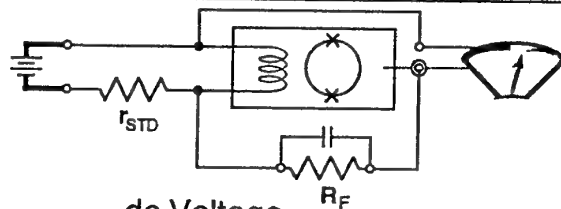




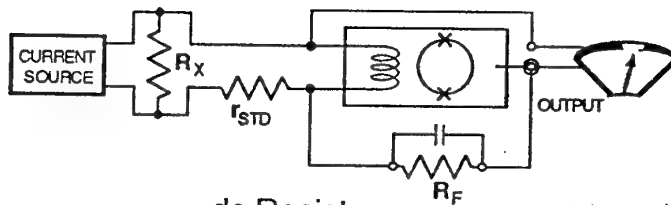
ac and dc Current



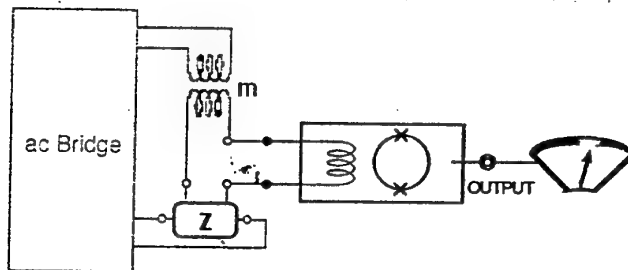
Magnetic Field



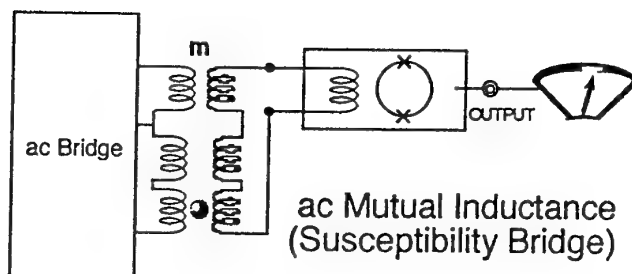
dc Voltage



dc Resistance



ac Resistance/Inductance Bridge



ac Mutual Inductance
(Susceptibility Bridge)

Applications

• Laboratory

Ammeter: 10^{-12} ampere/ $\sqrt{\text{Hz}}$
Voltmeter: 10^{-14} volt
Ohmmeter: $10^{-12} \Omega$
Mutual/Self Inductance: 10^{-12} henry
Magnetic Susceptibility: 10^{-10} emu & single electron spins
Magnetic Fields: 10^{-15} tesla/ $\sqrt{\text{Hz}}$
Nuclear Magnetic Resonance

• Geophysical

Oil Exploration
Airborne Exploration Systems
Oceanographic Measurements

• Biomedical

Studies of the Brain—**Neuromagnetism**
Studies of the Heart—Magnetocardiography
Liver, Lung, Intestines, other biological activity

• NDE

Defect Detection in Ferrous and Non-Ferrous Metals
Insulating Material Analysis
Infrastructure (Bridges, Runways, Buildings)
Aerospace

Magnetic Microscopy

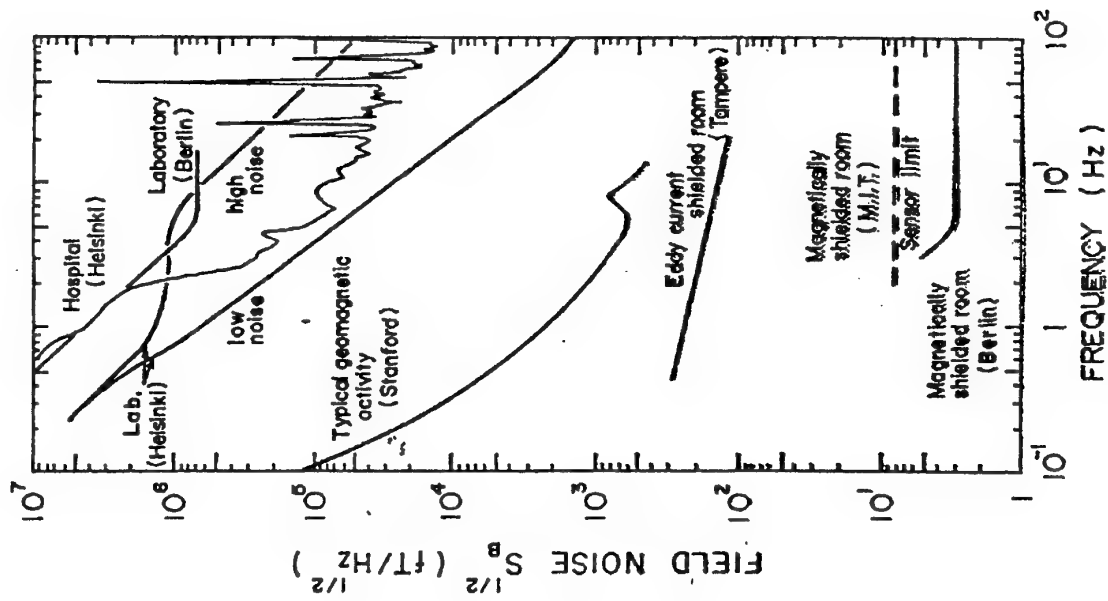
• Military

Mine Detection and Unexploded Ordinance (UXO)
Submarine Communication and Detection

• non-SQUID Electronics *(but interesting)*

Digital switching
Cellular filters
NMR and MRI receiver coils

Environmental Noise



Impact of High Temperature Superconductivity

- 1986: Discovery of High Temperature Superconductivity
- Higher Operating Temperatures and Reduced Cooling Requirements
- Primarily Thin-Film Fabrication (not really HTS, but parallel development)

• Positives

- Simplified cryogenics
ratio of latent heats/unit volume
(LN_2/LHe) ≈ 50
single-stage closed cycle cooling possible
- Reduced size and operating costs

• Negatives

- Noise power proportional to temperature
but at acceptable levels: 10^{-30} J/KHz
- Planar devices suitable only for:
Magnetometers: B_x
planar gradiometers: $\frac{\partial B_z}{\partial x}$
- Need $< 10^{-12} \Omega$ joint resistances for dc response $\frac{\partial B_z}{\partial z}$
Problem of interconnects for 3D structures



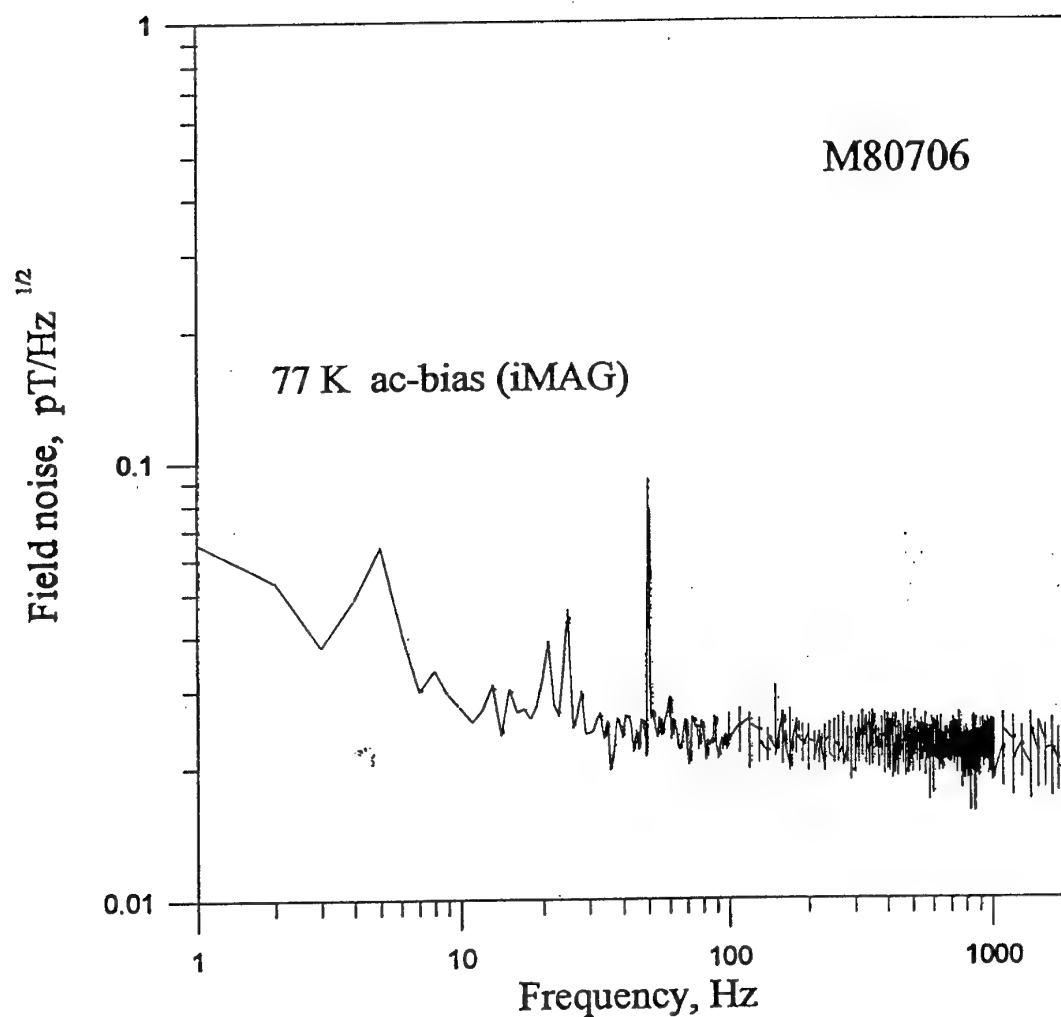
HTS DC-SQUID flip-chip magnetometers



Multilayer flux transformer on 10 mm x 10 mm SrTiO_3 substrate and encapsulated dc-SQUID magnetometers. The magnetometers are fixed on standard dc-SQUID packages (axial and 90°) designed for operation together with iMAG electronics.



HTS DC-SQUID flip-chip magnetometers



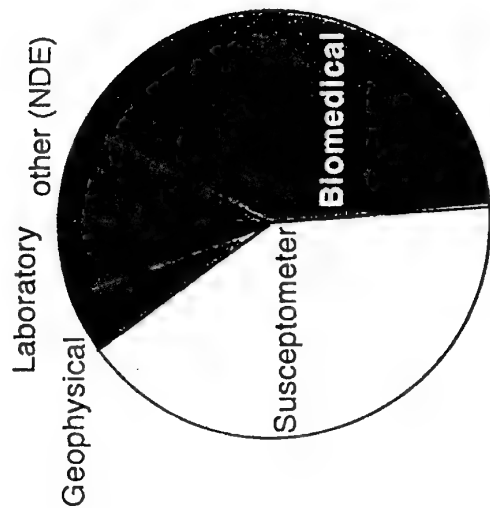
An example of a noise measurement with the flip-chip magnetometer, having a 8 mm x 8 mm pick-up loop of the flux transformer, measured inside a four layers μ -metal shield.

Product Costs

- **Laboratory**
 - Basic measurement system \$10,000
 - SQUID susceptometer \$150,000
- **Geophysical**
 - 3-axis HTS magnetometer \$40,000
 - Rock magnetometer \$150,000
- **Biomedical**
 - 150 channel neuromagnetometer \$2,000,000
 - Single channel biomagnetometer \$50,000
 - Liver-Iron biosusceptometer \$750,000
 - Custom biomagnetometer \$100,000 - 300,000
- **NDE**
 - Basic measurement system \$20,000
 - Magnetic microscope \$380,000
 - Custom NDE system \$50,000 - 500,000

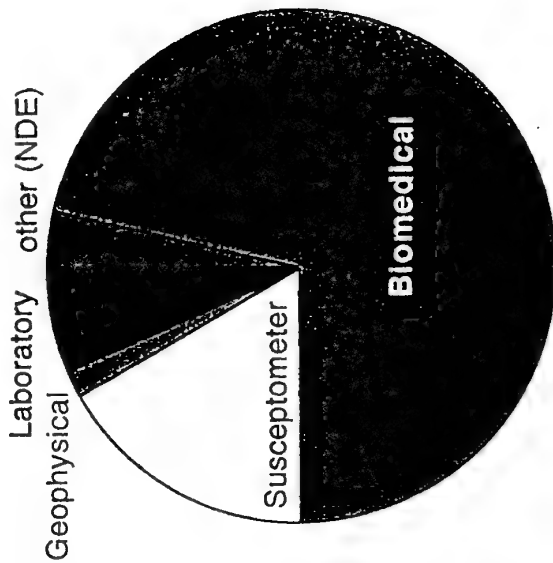
Market Sizes

1989



25 M\$

1998



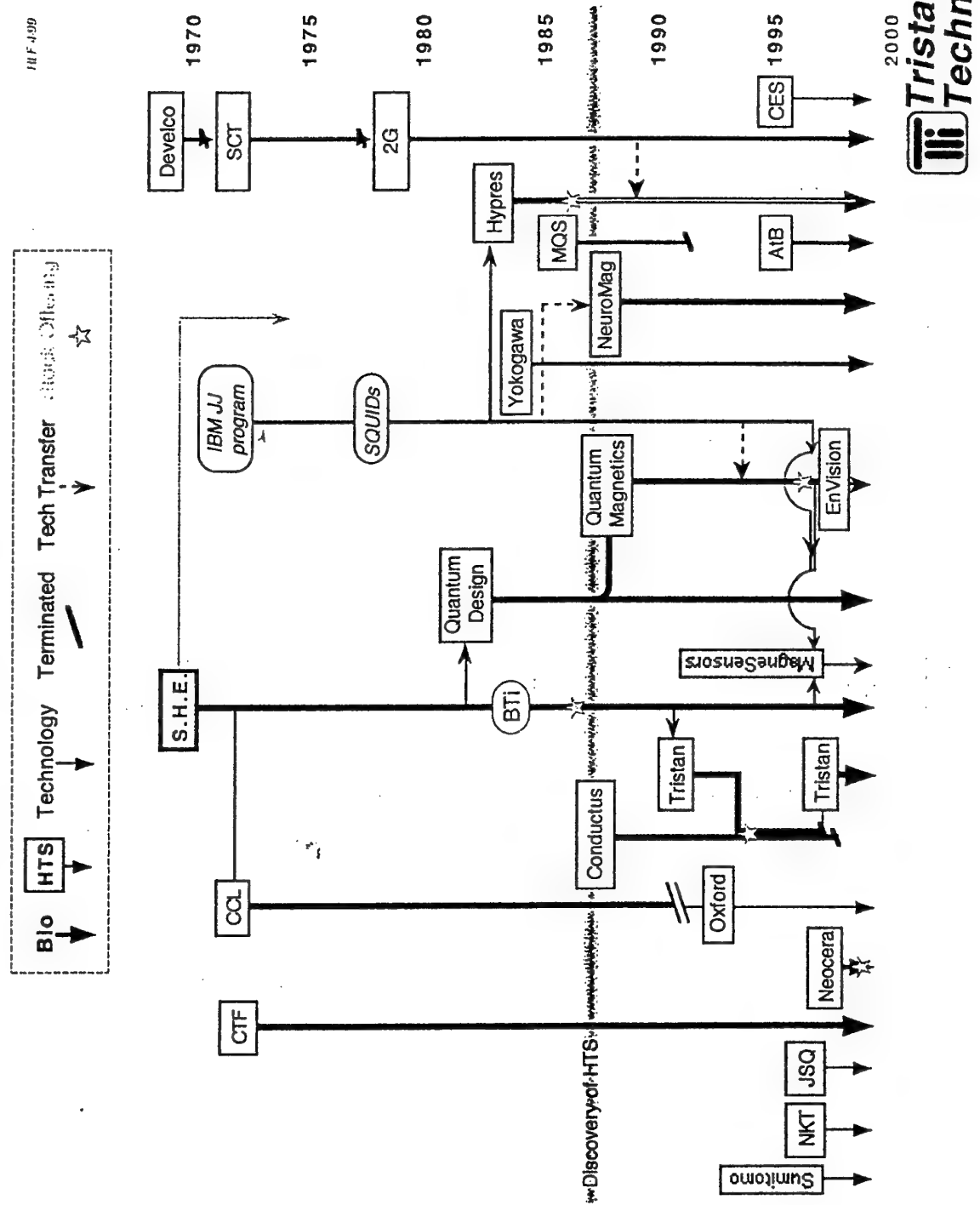
30 M\$

- SQUID susceptometer market saturated
- 1999 Biomagnetism market increasing
60+ whole head systems installed
as many as 10 more in 1999
- SQUID NDE (primarily Microscopy)
could be 10 M\$ in 2000

TimeLine

1962	Josephson Junction
1964	1 st SQUID
1970	1 st Commercial rf SQUID
1974	Toroidal rf SQUID (ruggedized)
1980	Hybrid (thin film) rf SQUID
1982	1 st Commercial dc SQUID
1984	Biomagnetism emerges
1986	High Temperature Superconductivity
1993	Mr. SQUID (1 st Commercial HTS device)
1994	1 st Commercial HTS SQUID

PH F 4.99



Corporate Types

- Type I
 - Large
 - > \$100,000,000
 - > 500 employees
 - Diversified Technologies
 - multiple manufacturing sites
 - Profitable
 - *IGC, Oxford*
- Type II
 - Moderate size
 - ~\$10,000,000
 - < 100 employees
 - Single underlying technology products
 - single manufacturing site
 - Profitable
 - Quantum Design, Neuromag
- Type III
 - Products centered around single technology
 - Venture Capital/IPO Funded
 - Funding based upon market prospects > \$100,000,000
 - Rapid growth after funding
 - > 100 employees
 - \$5,000,000 - 10,000,000 annual expenditures
 - Retrenchment Phase
 - Market **Non-Acceptance** of Product
 - < 50 employees
 - more realistic market approach (*hopefully*)
 - BTi, Conductus, Hypres

Obstacles

- **Perceived**

- Need for cryogenics
- Environmental noise
 - Need for shielding or sophisticated noise rejection
- Motion induced noise
 - SQUIDS are vector devices
- Cost

- **Applications**

- Science establishes capability
- Users establish need

- **Market Resistance**

- Too often Technology Push, rather than Market Pull

- **Must Establish Need!**

- Biomagnetism: Compelling Clinical Requirement
- Industrial: Capability that saves user many M\$

Conclusions

need to state influence of outside capital
what does it take to become a type I?
Product saturation vs. expanding markets

- SQUIDS offer *Significant* Technical Advantages
- There are Product Applications
- Only a “killer” Application gets you to Type I
- If the Market is Small, a Type II Company is appropriate

SQUIDS for Geomagnetic Exploration

A.I. Braginski

*Institut für Schicht- und Ionentechnik (ISI)
Forschungszentrum Jülich GmbH (FZJ), D-52425 Jülich
(Retired)*

Partial support: BMBF Project No. 13 N 6527

Acknowledgements

Leading Project Collaborators:

M. Bick, K.-D. Husemann, R. Otto, G. Panaitov, N. Wolters, Y. Zhang and E. Zimmermann

Project Partners:

GERMANY: IPHT-Jena, Metronix GmbH, Tech. Univ. Berlin; CHINA: IGGE, Univ. of Peking

Unpublished Data:

Courtesy of C. Foley et al. CSIRO, Australia

Outline

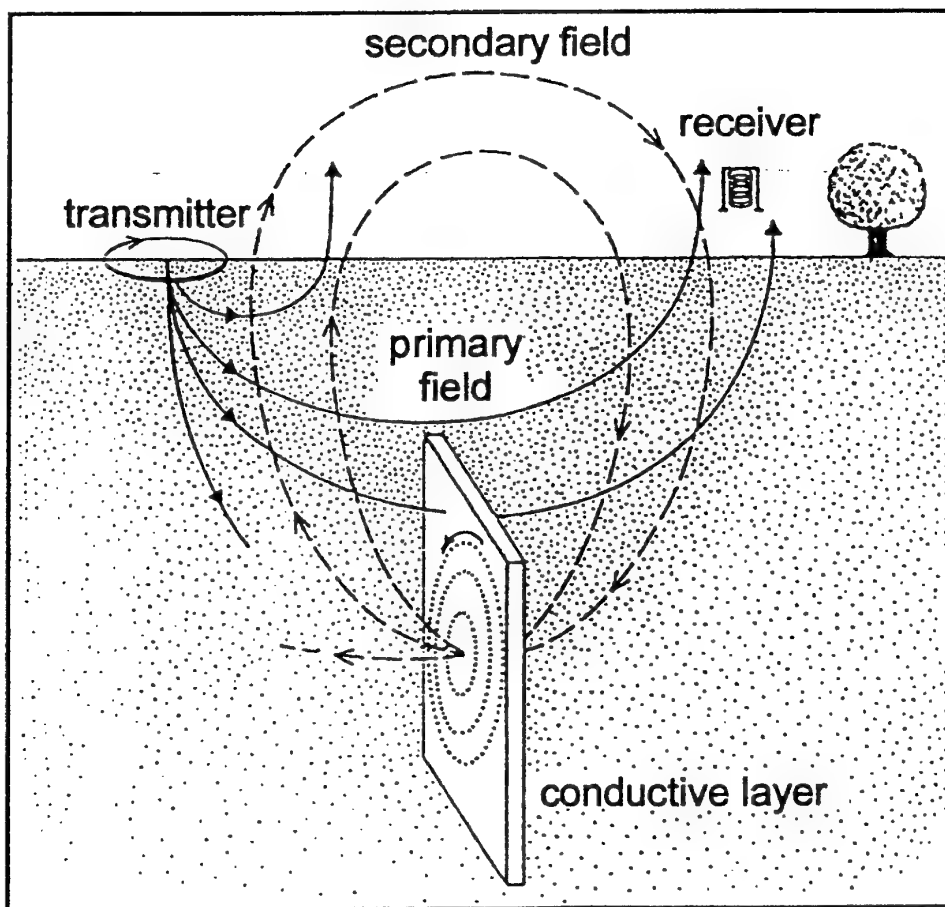
- **Introduction**
- **Electromagnetic Methods of Geophysical Exploration**
- **Areas of Possible SQUID Applications in Geomagnetism**
- **Performance Requirements for SQUID Magnetometers**
- **History of LTS SQUID Uses in Geophysics**
- **Status of HTS SQUID Developments, rf and dc Magnetometers**
- **HTS SQUID Field Data**
- **Conclusions & Outlook**



Principle of EM Methods in Geophysics

target parameter: electrical ground conductivity

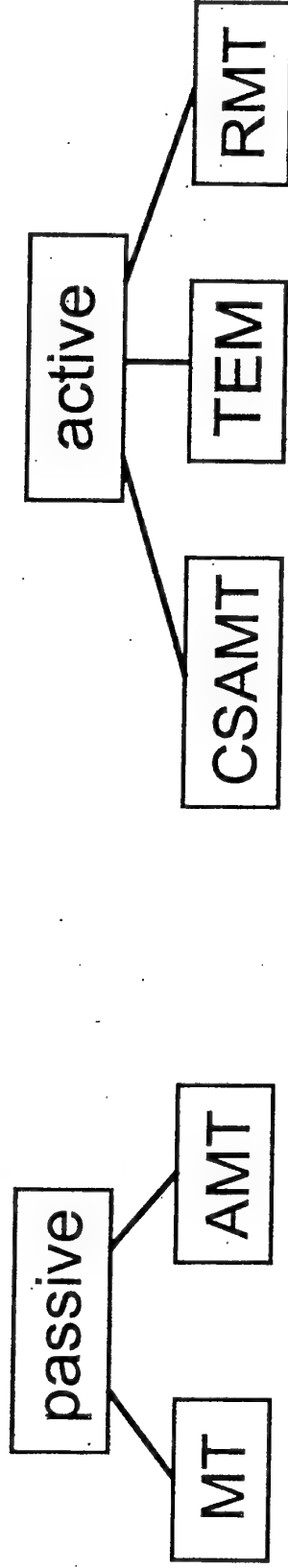
distinguish geological structures
by differences in conductivity



$$\text{skin depth } z \sim \sqrt{\frac{1}{\sigma \cdot f}}$$

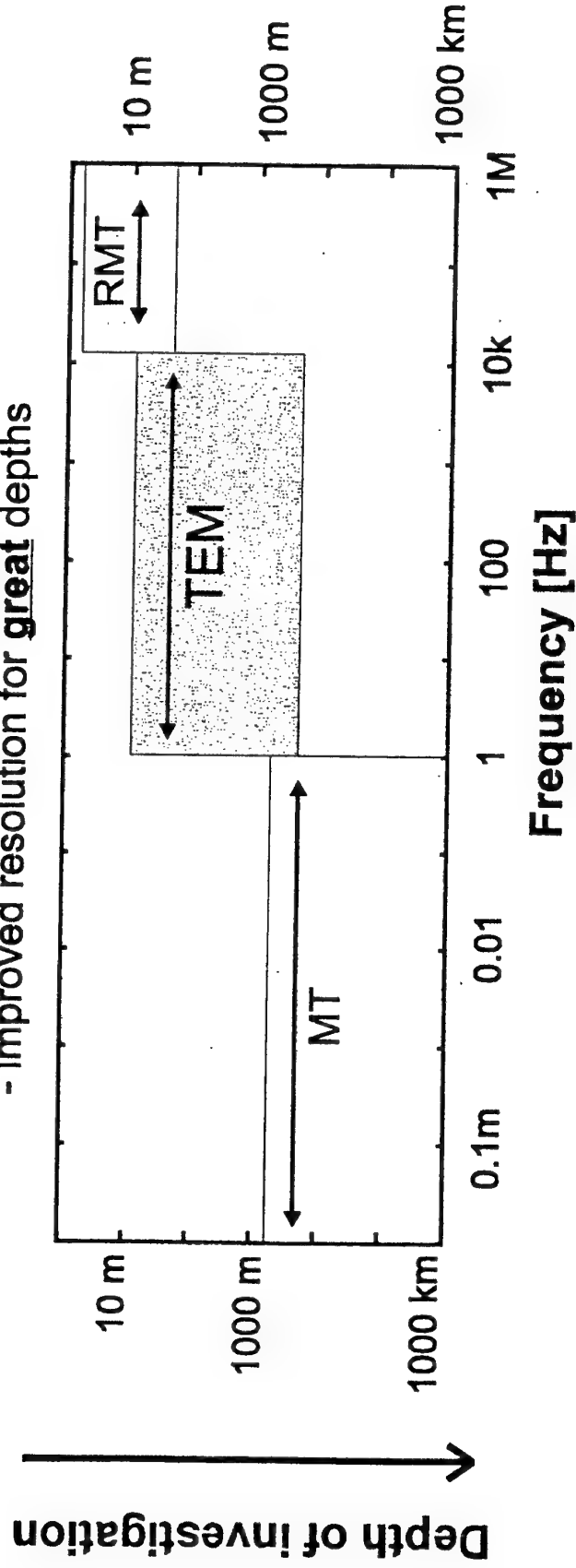
σ = conductivity; f = frequency

Electromagnetic Methods in Geophysics



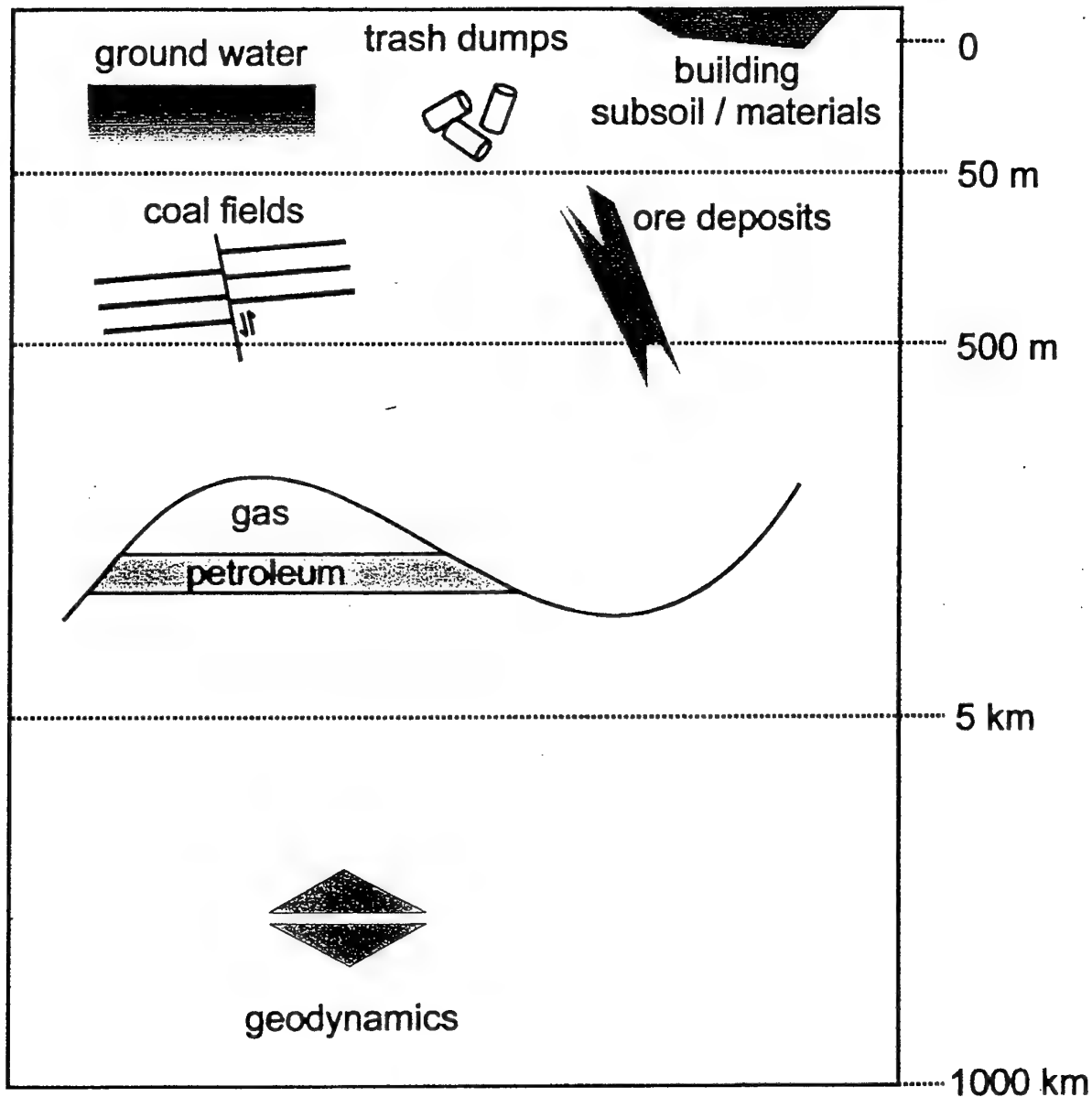
claim: - one sensor for all methods

- improved resolution for **great** depths





Application of Electromagnetic Methods for Geological Investigations



Electromagnetic Methods of Geophysical Sounding

Time Domain:

- * Transient Electromagnetic Method (TEM)**
- * Long-Offset TEM (LOTEM)**

Frequency Domain:

- * Magnetotelluric (MT, AMT)**
- * Controlled-Source MT, AMT (CSMT, CSAMT)**
- * Very Low Radio Frequency Resistivity (VLF-R)**
- * Radiomagnetic Sounding (RMS)**

Magnetotellurics

- Natural or controlled source EM excitation, from 10^{-3} to $> 10^3$ Hz
- Determine at earth surface:

$$Z_{xy}(\omega) = \mu_0 \mu E_x(\omega) / B_y(\omega)$$

$(\mu \approx 1)$

- For a homogeneous earth:

$$\rho_{xy} = 1 / \mu_0 \mu \omega |Z_{xy}(\omega)|^2$$

- For inhomogeneous subsoil one can use the apparent resistivity $\rho_a(\omega)$:

$$\rho_a \approx 0.2t [E_x / H_y]^2$$

where: ρ_a [Ω], t [sec], E_x [mV/km], H_y [nT]

- Depth of penetration:

$$p \approx 1/2\pi(10\rho_a t)^{1/2}$$

Recording Truck

Colls

E_y

H_y

H_z

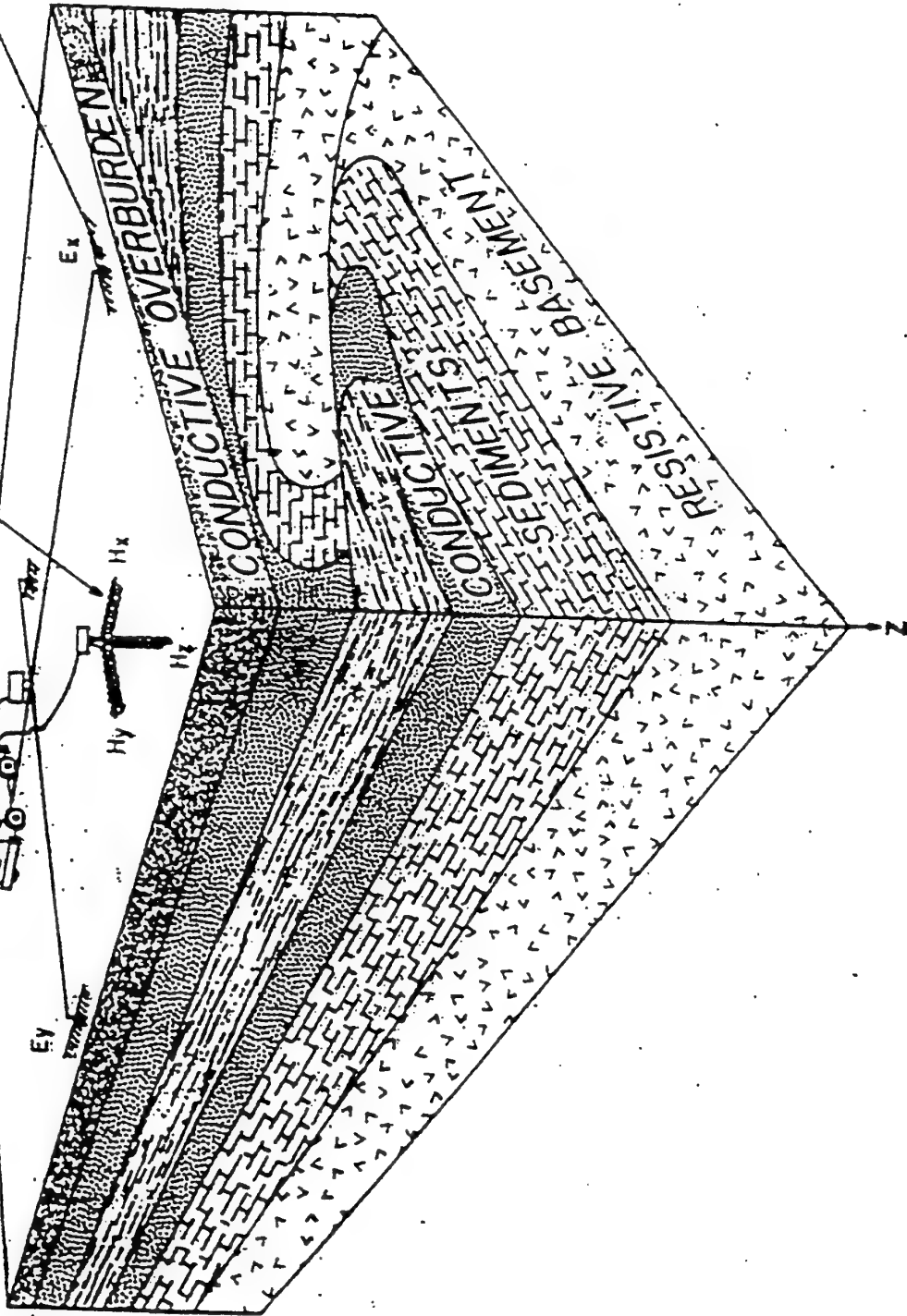
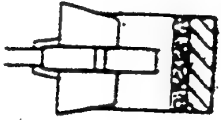
H_x

E_x

Y

Z

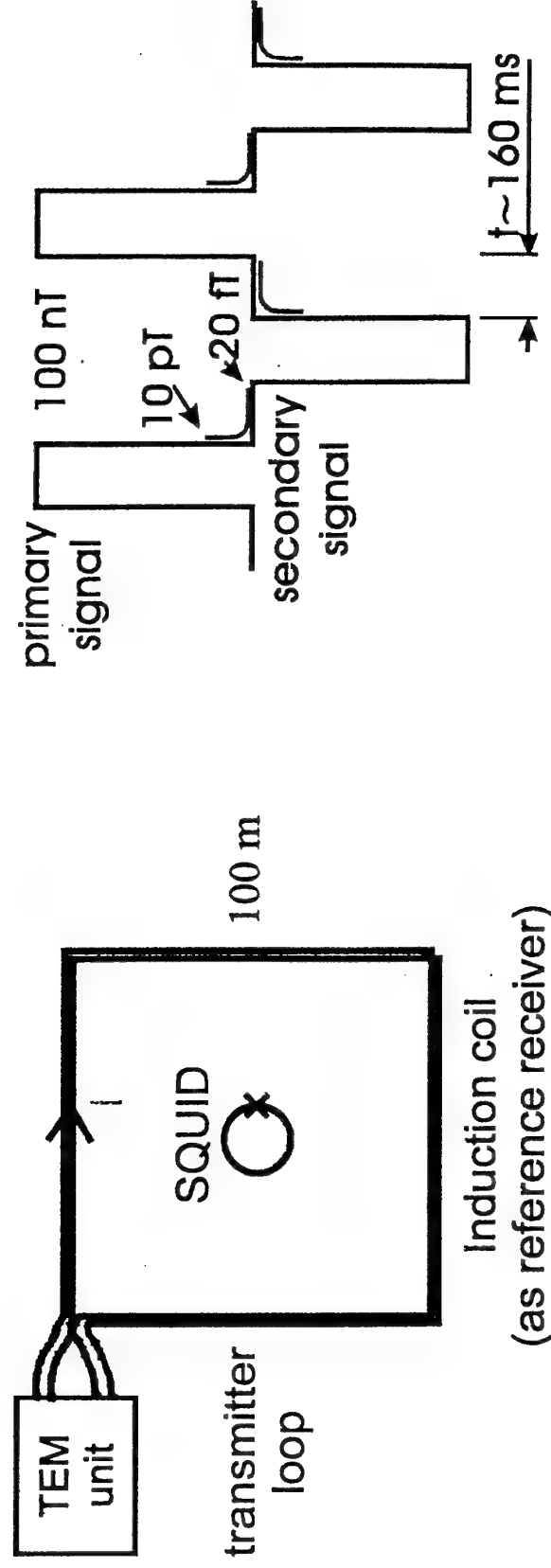
Cd - CdCl₂
Porous Pot
Electrodes





Principle of Transient Electromagnetics (TEM)

- transmitter generates magnetic field in the ground
- decay of secondary signal measured by SQUID
- improvement of SN-ratio by using bipolar transmitter signal

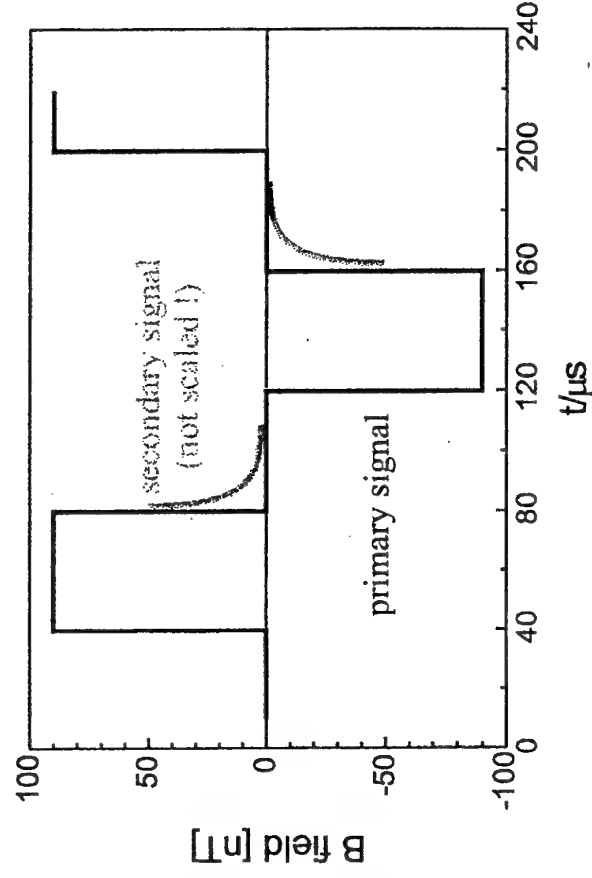
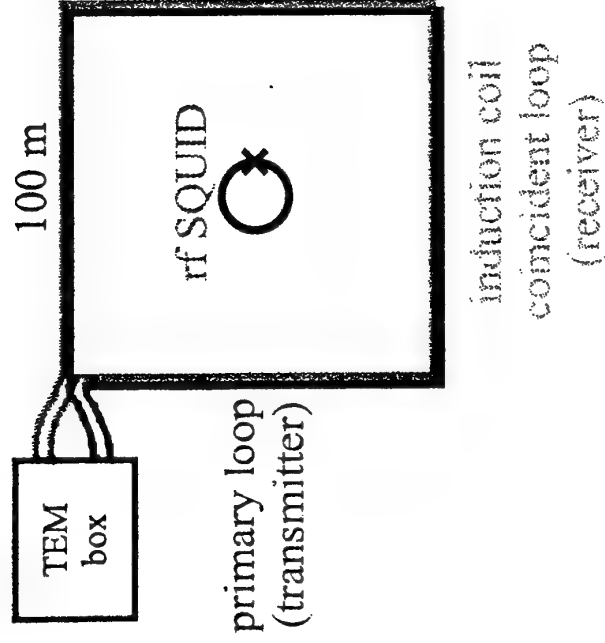


Principle of Transient Electromagnetics (TEM) Measurements in Geophysics

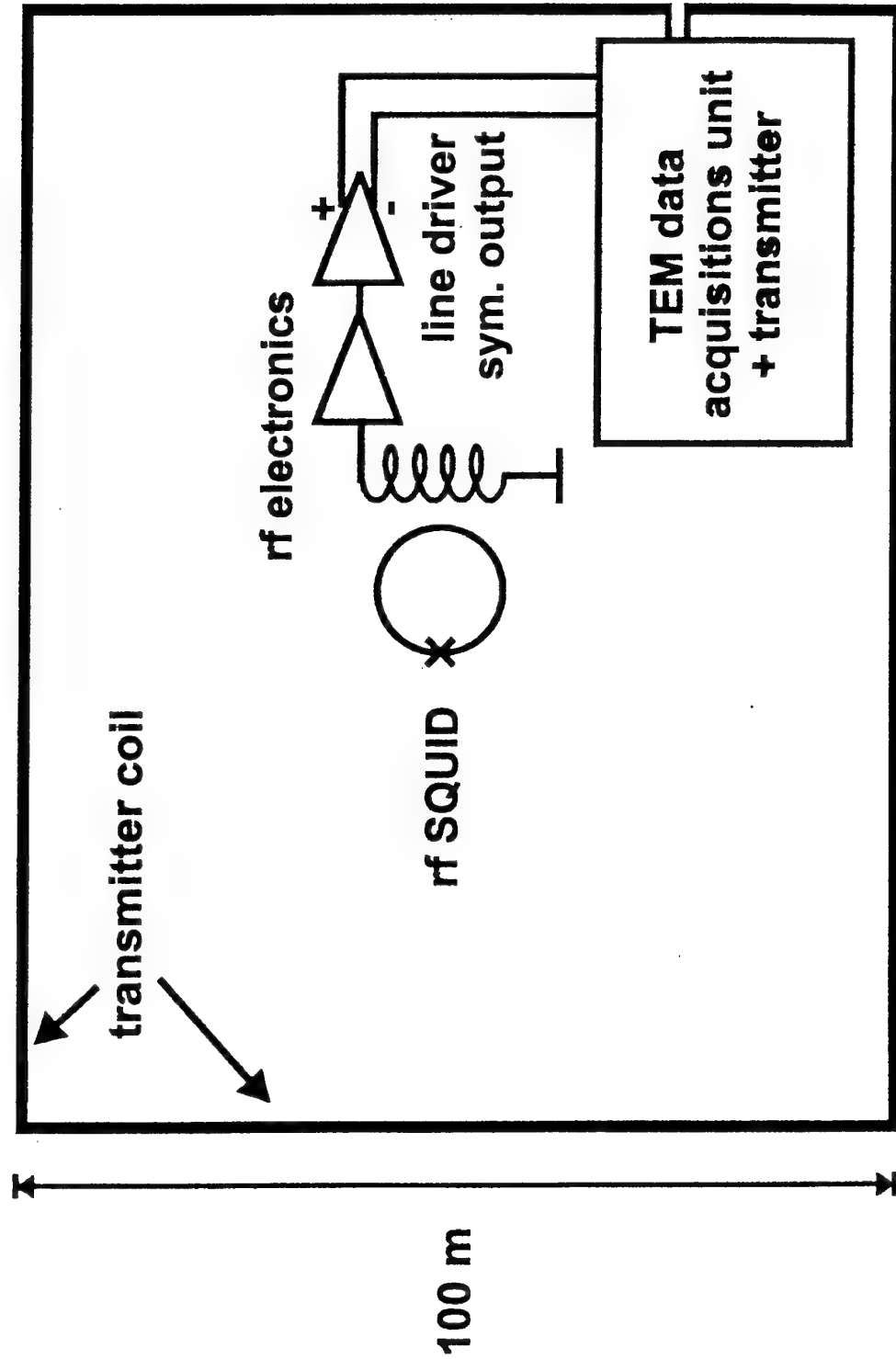
decay of secondary field measured by rf SQUID

for homogeneous halfspace expected:

$$B \sim t^{-1.5}$$

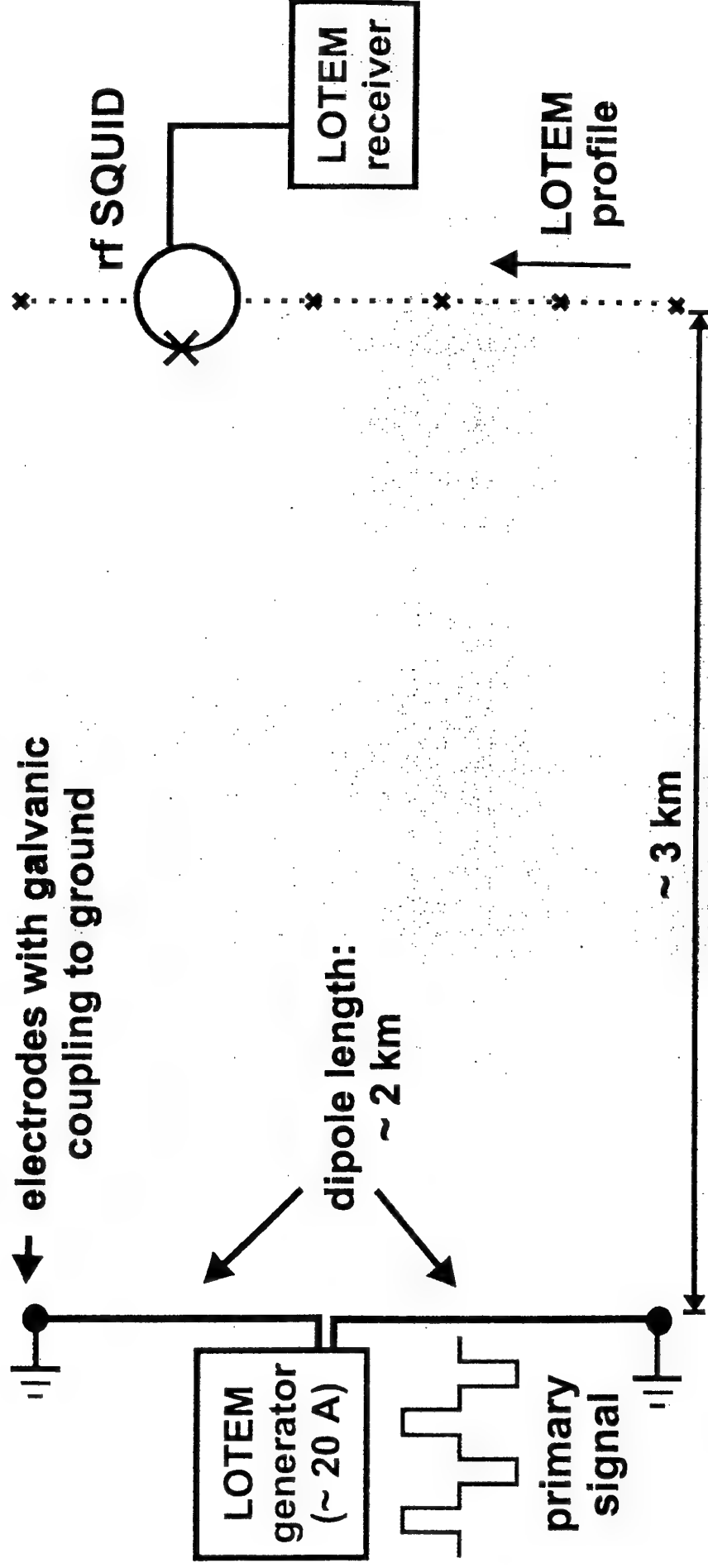


Setup of TEM Field Trial



Principle and Setup of LOTEM

- Investigation depths: several km
- Targets: oil and ore deposits



The Bible:

**Electromagnetic methods in Applied
Geophysics – Applications, Parts A, B**

Editor:

M.N. Nabighian

First Published in 1991 (last edition 1996) by:

**Society of Exploration Physicists
P.O.Box 702740, Tulsa Oklahoma 74170-2740**

Possible Applications of SQUID in Geomagnetism

- **Paleomagnetism (Rock Sample Magnetometry)**
- **Prospecting/Surveying for Ore, Coal, etc. Deposits**
- **Prospecting for Oil Deposits**
- **Exploration for Geothermal Energy**
- **Small-Area Prospecting for Water, Buried Waste, Archeological Objects**
- **Volcanic Eruption and Earthquake Prediction**
- **Fluid Interface Detection**

Source:

SQUID Applications to Geophysics

Editors:

H. Weinstock & A.C. Overton

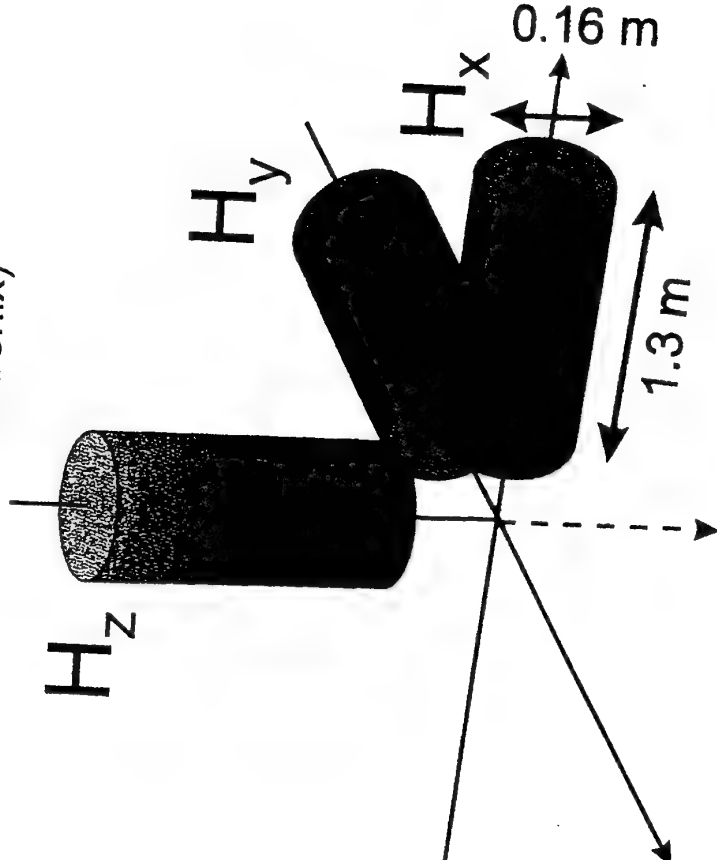
Published in 1981 by:

**Society of Exploration Physicists
P.O.Box 702740, Tulsa Oklahoma 74170-2740**

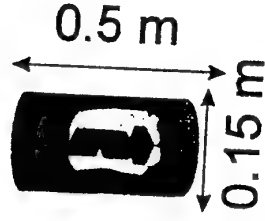
Advantages of HTS SQUIDS

Size:

triple of induction coils
(e.g. product of Metronix)



triple of
HTS SQUIDS



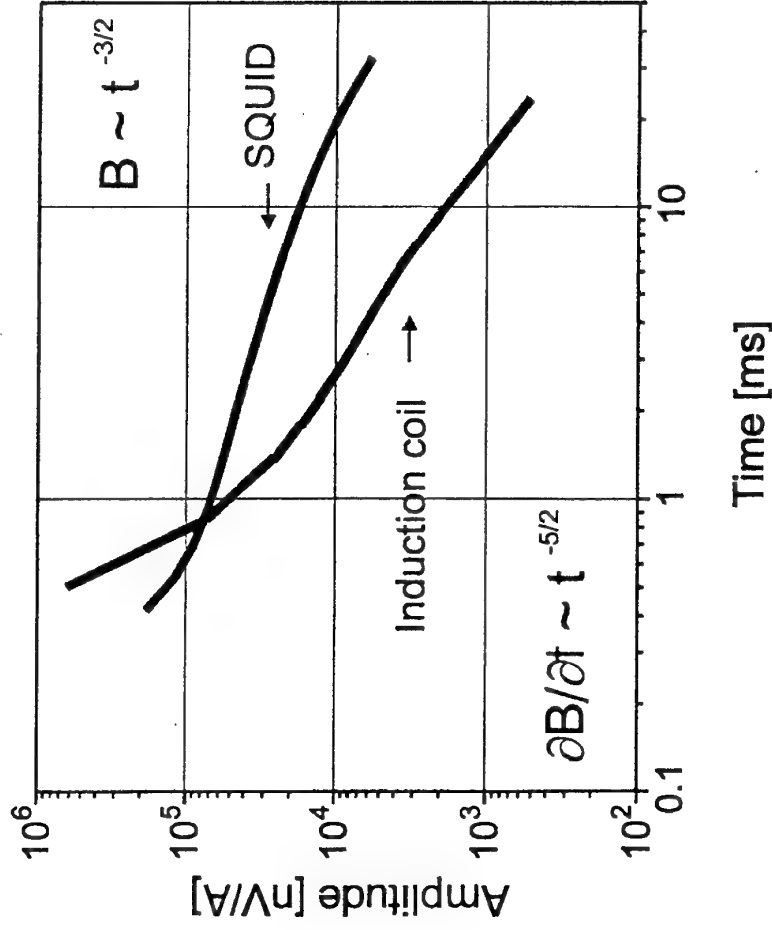
- compact, low weight:
 - easy handling
 - borehole potential
- broadband sensor (dc - 20 kHz / 10MHz)
- high sensitivity at low frequencies
- B-field sensor

Requirements:

- field proven
- dyn. range > 120db
- slew rate > 1mT/sec



TEM Method: Principle Advantage of SQUID



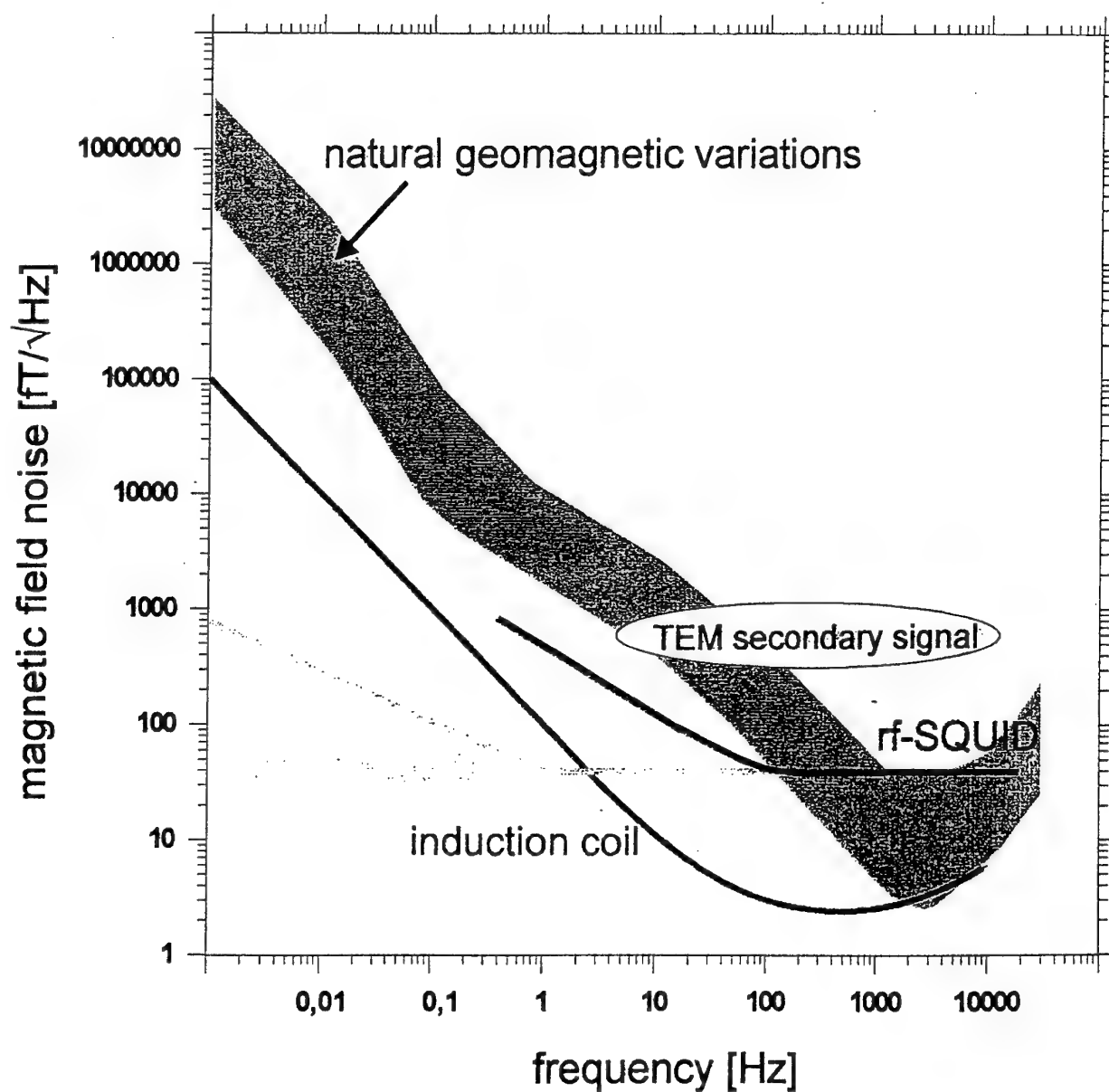
▪ **Disadvantage of coil: $\partial B/\partial t$ receiver**
 depth of investigation $z \propto \left(\frac{I \cdot A}{\sigma \cdot \eta_v} \right)^{1/5}$

▪ **Advantage of SQUID: B-field sensor**
 depth of investigation $z \propto \left(\frac{I \cdot A}{\eta_B} \right)^{1/3}$

[Spies, 1989]



Magnetic field noise for HTS rf SQUID and induction coil



Geomagnetic Exploration

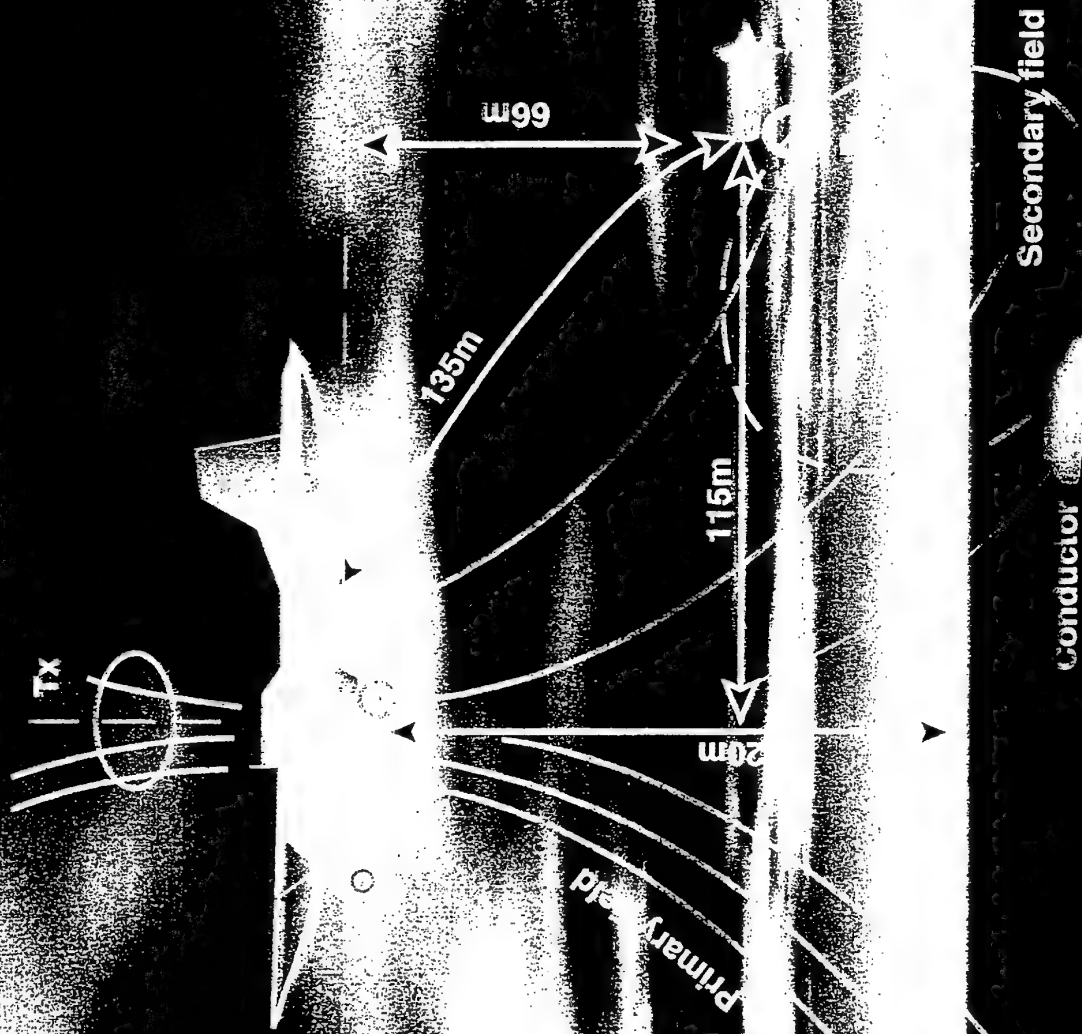
Objective:

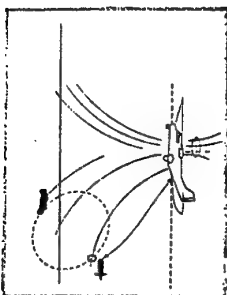
Improve portability, versatility, also attain mobility, beyond limitations of conventional induction coil equipment, but without sacrificing and possibly improving sensitivity of detection

EM Methods Investigated:

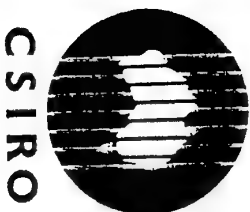
- **Transient EM (time domain)**
- **Controlled-source audio magnetotellurics (frequency domain)**
- **Radiometric detection of water & environmental waste**

System Geometry

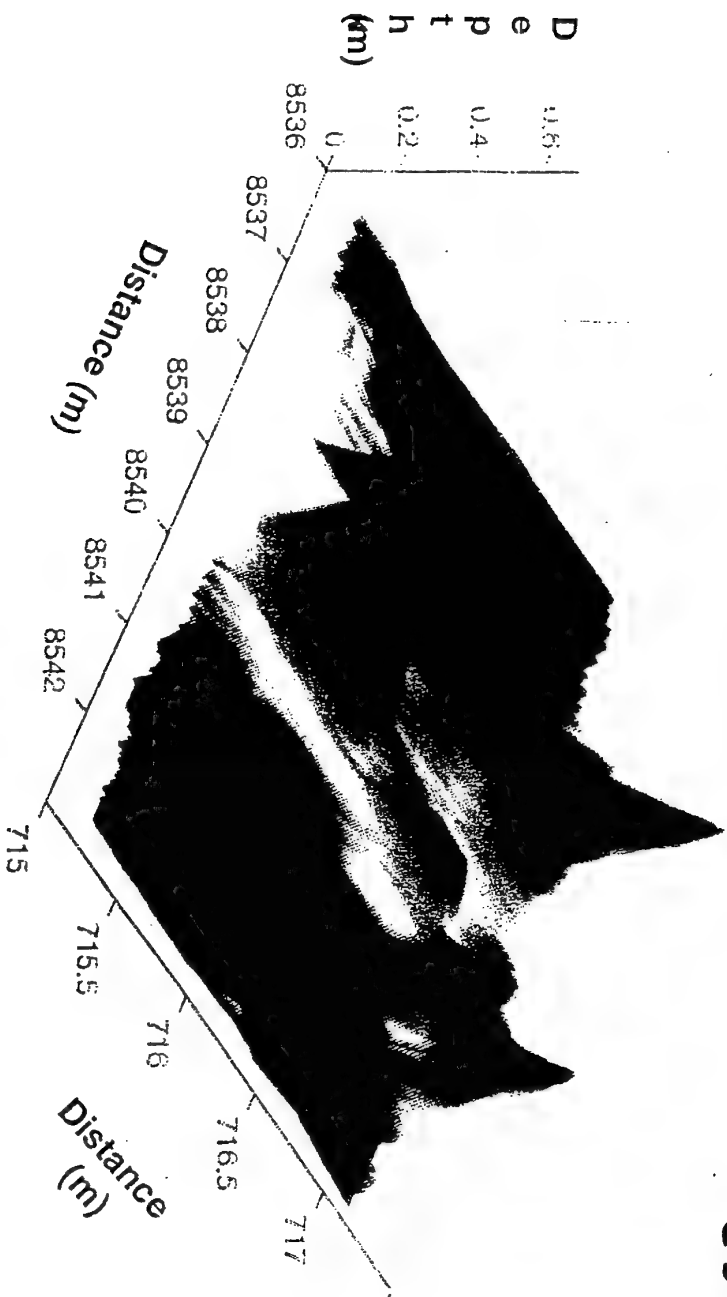




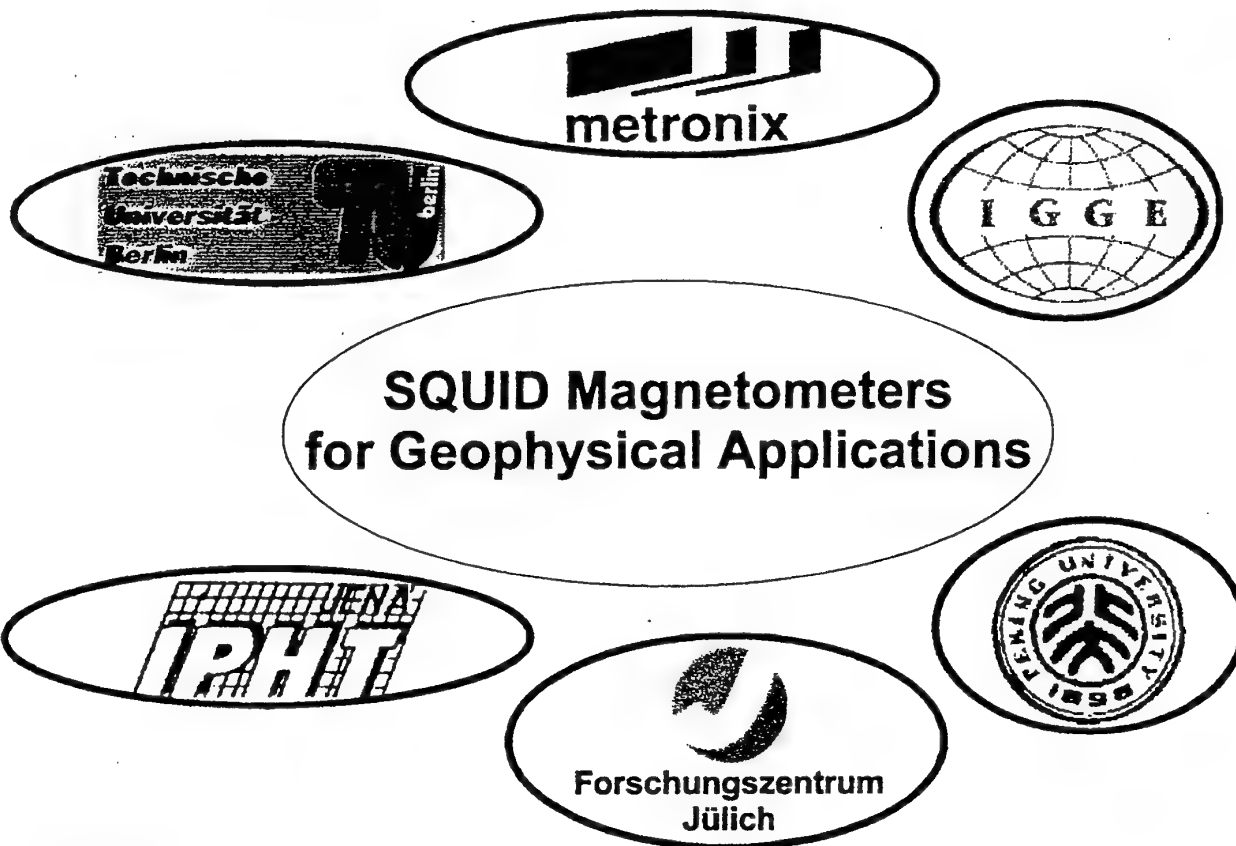
AIR BORNE RESULTS (Conductivity)



CSIRO



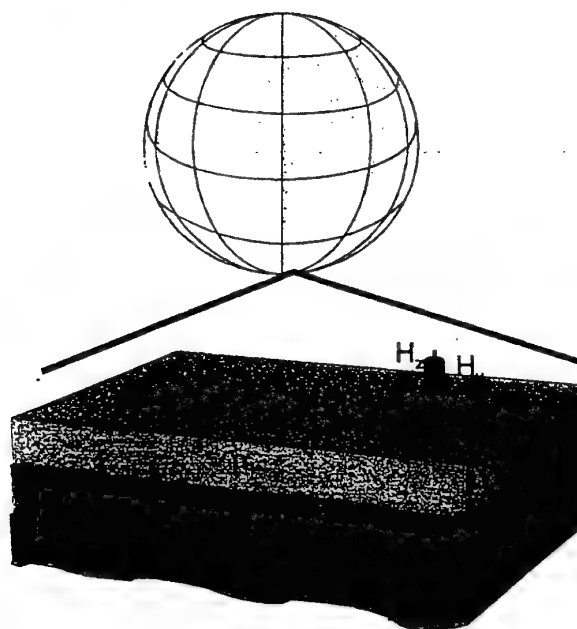
Project Supported by German Government (BMBF)



Objectives:

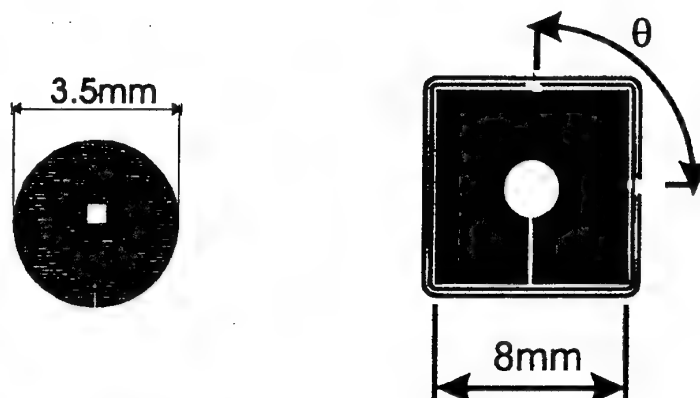
Development of a compact, broadband vector magnetometer

Demonstration of geophysical exploration





Sensor Set-up of HTS rf SQUID Vector Magnetometer



- **sensor:** rf washer SQUID and coplanar resonator in flip-chip configuration

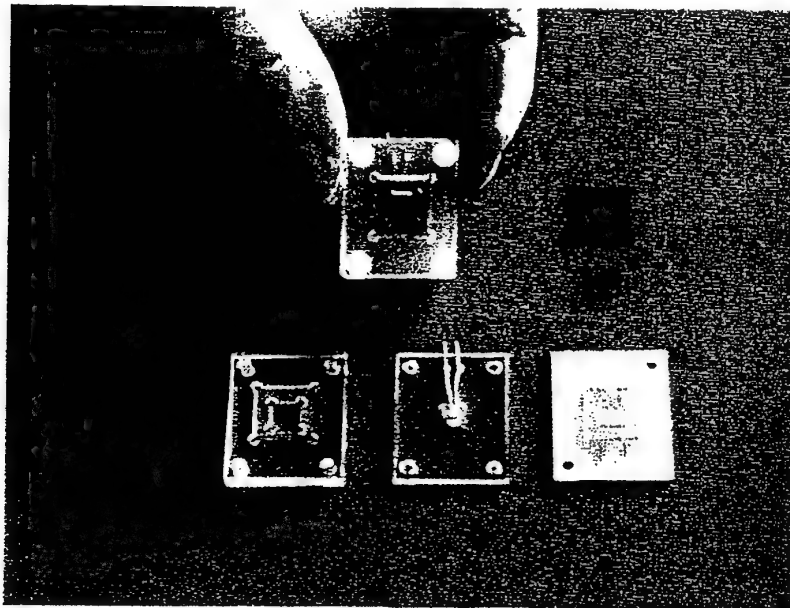
SQUID:

- YBCO washer: $\varnothing = 3,5\text{mm}$
- loop: $100 \times 100 \mu\text{m}^2$, $10 \times 500 \mu\text{m}^2$
- junction type: step edge junction
- junction width: $4 \mu\text{m}$

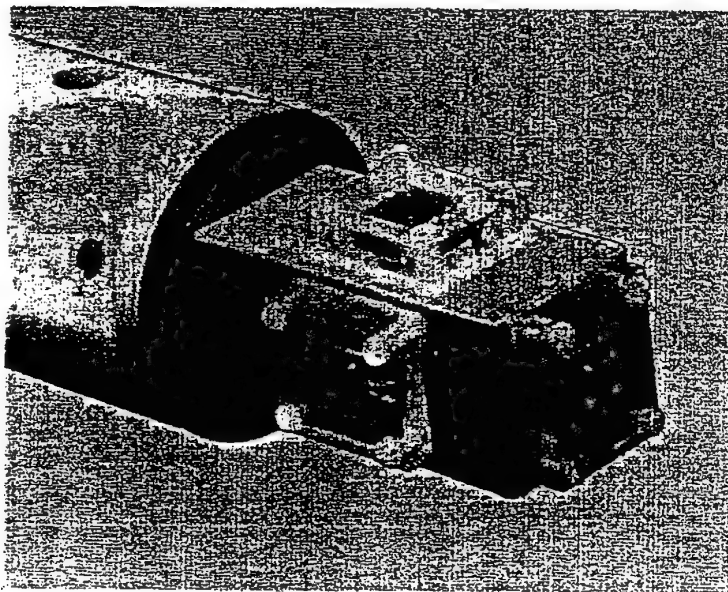
resonator:

- coplanar: $\varnothing = 8\text{mm}$ on 1cm^2 substrate
- frequency: $650 \text{ MHz} - 1 \text{ GHz}$
- $\partial B / \partial \Phi = 3,9 \text{ nT} / \Phi_0$, $2,7 \text{ nT} / \Phi_0$

Sensor Module of HTS rf SQUID Vector Magnetometer [YBCO]



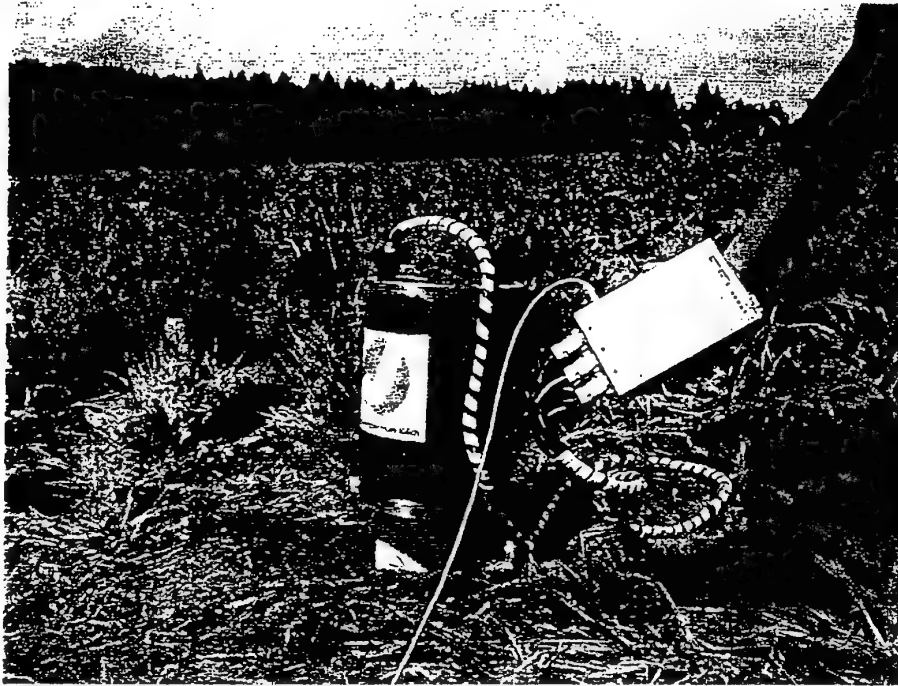
rf SQUID, coplanar resonator and planar coupling coil
integration of heater to eliminate trapped magnetic flux



triaxial sensor head

3-axis HTS rf SQUID Vector Magnetometer

Field Trial at Erbsdorf, Oberpfalz



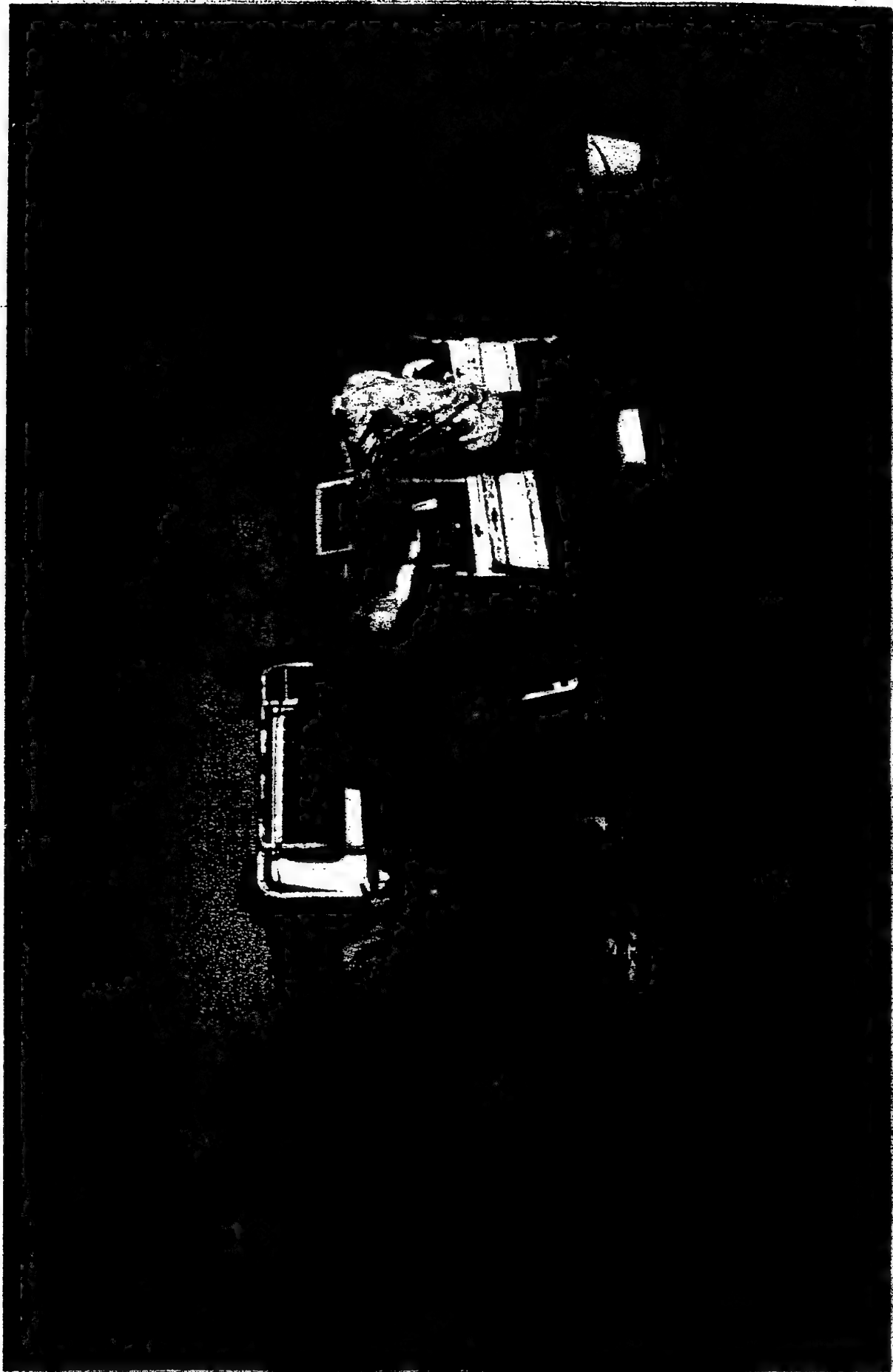
System includes heater and automatic adjustment of SQUID parameters; well shielded against rf noise



TEM Survey with SQUID System

Cloncurry, Australia, October 1998







Improved HTS SQUID Vector Magnetometer Presented at the Industrial Geophysical Exhibition SEG '98



Booth # 2660 of Metronix GmbH



Characteristics of HTS rf SQUID Vector Magnetometer

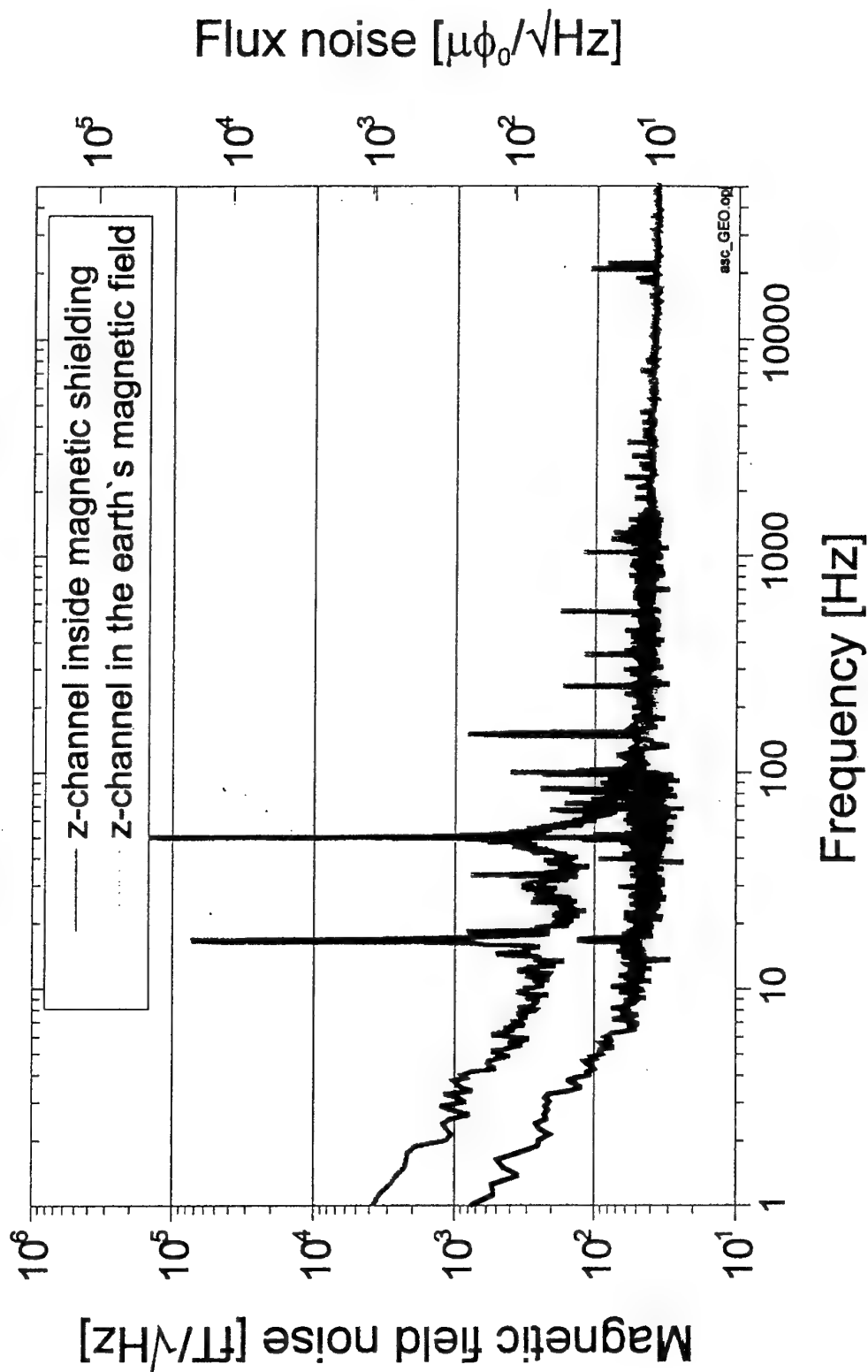
- **sensor set up:** orthogonal, capsulated
 - **bandwidth:** dc – 20 kHz
 - **dynamic range:** > 130 dB
 - **slew rate:** ~ 2mT/s [$\sim 5 \times 10^5 \Phi_0/s$]
 - **cross talk:** < 0.5 %
 - **hold time of dewar:** > 30 h
 - **implemented heater**
-
- **field resolution:**
 - white noise 40 fT/ $\sqrt{\text{Hz}}$ [typical]
 - 1/f – onset @ 100 Hz [best channel]

⇒ **Requirements for TEM fulfilled**

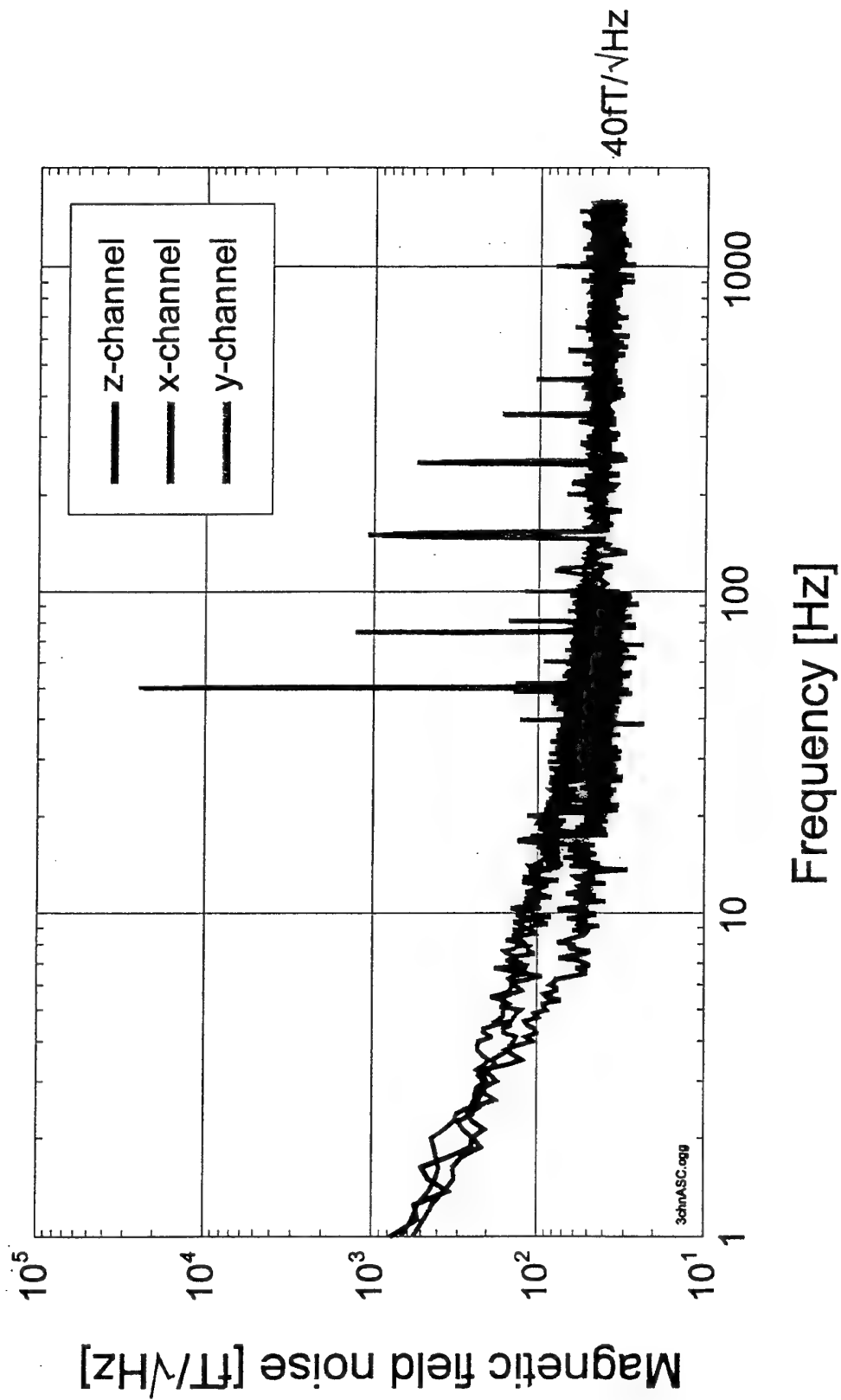
⇒ **Stable operation of all 3 channels in
urban environment proved**

Noise Spectra of Vector Magnetometer (Z-channel) in and Outside Magnetic Shielding

1/f-onset @ ~ 7 Hz in shielding
@ ~ 100 Hz outside shielding

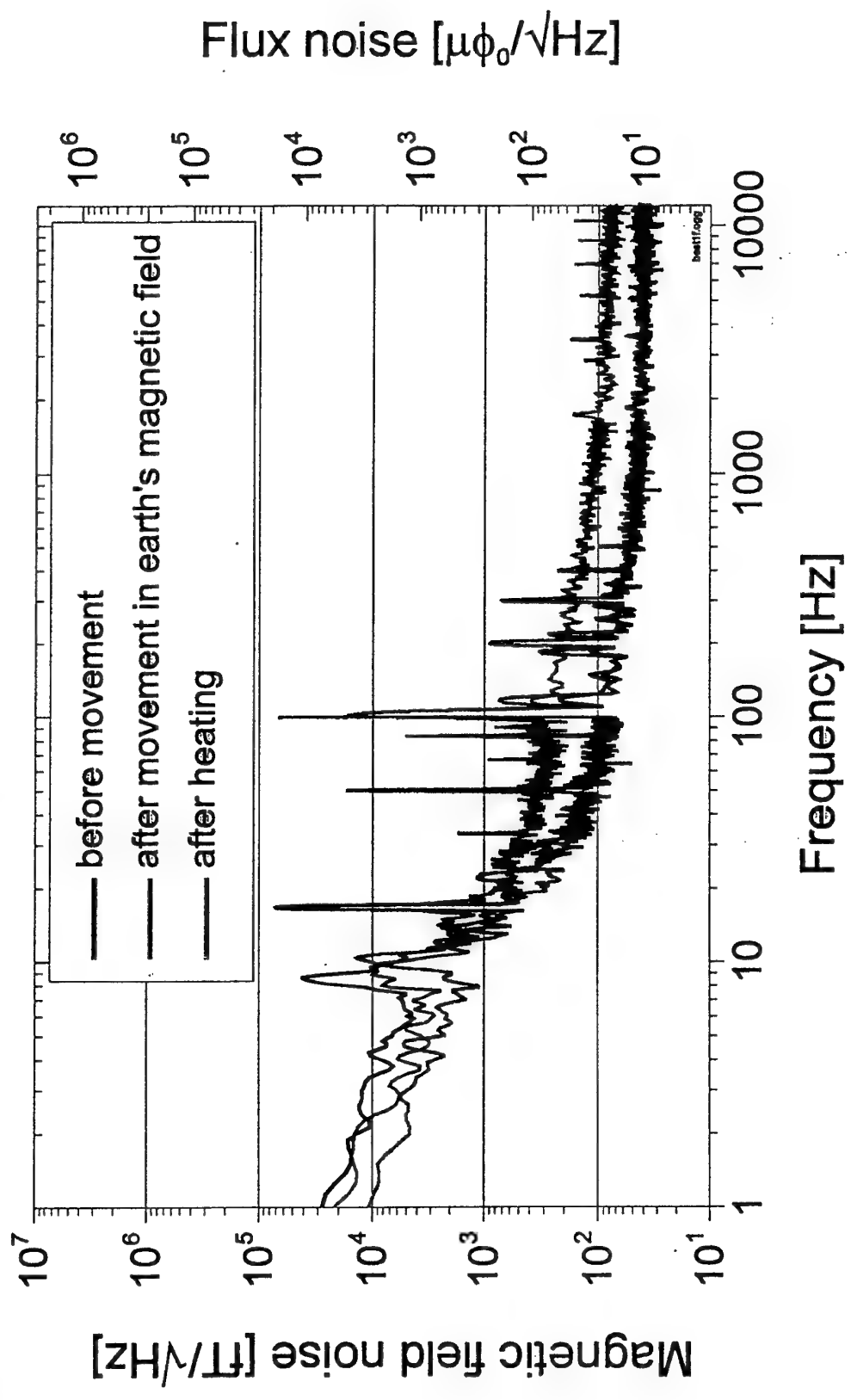


Noise Spectra of Vector Magnetometer Inside 3-layer μ -metal Shielding

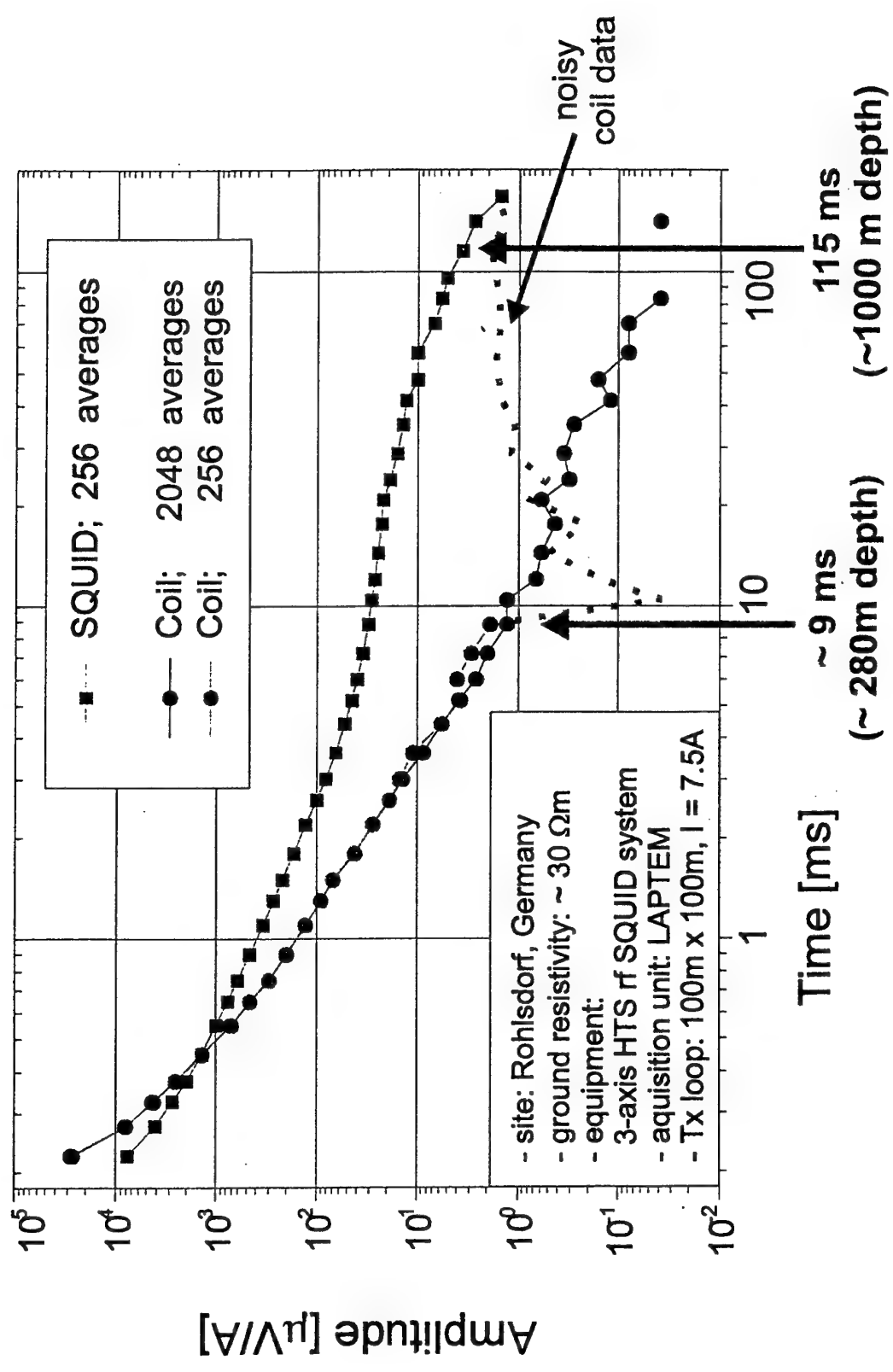


Performance of Heater:

Noise Spectra Before and After Heating (X-channel) During Field Trial

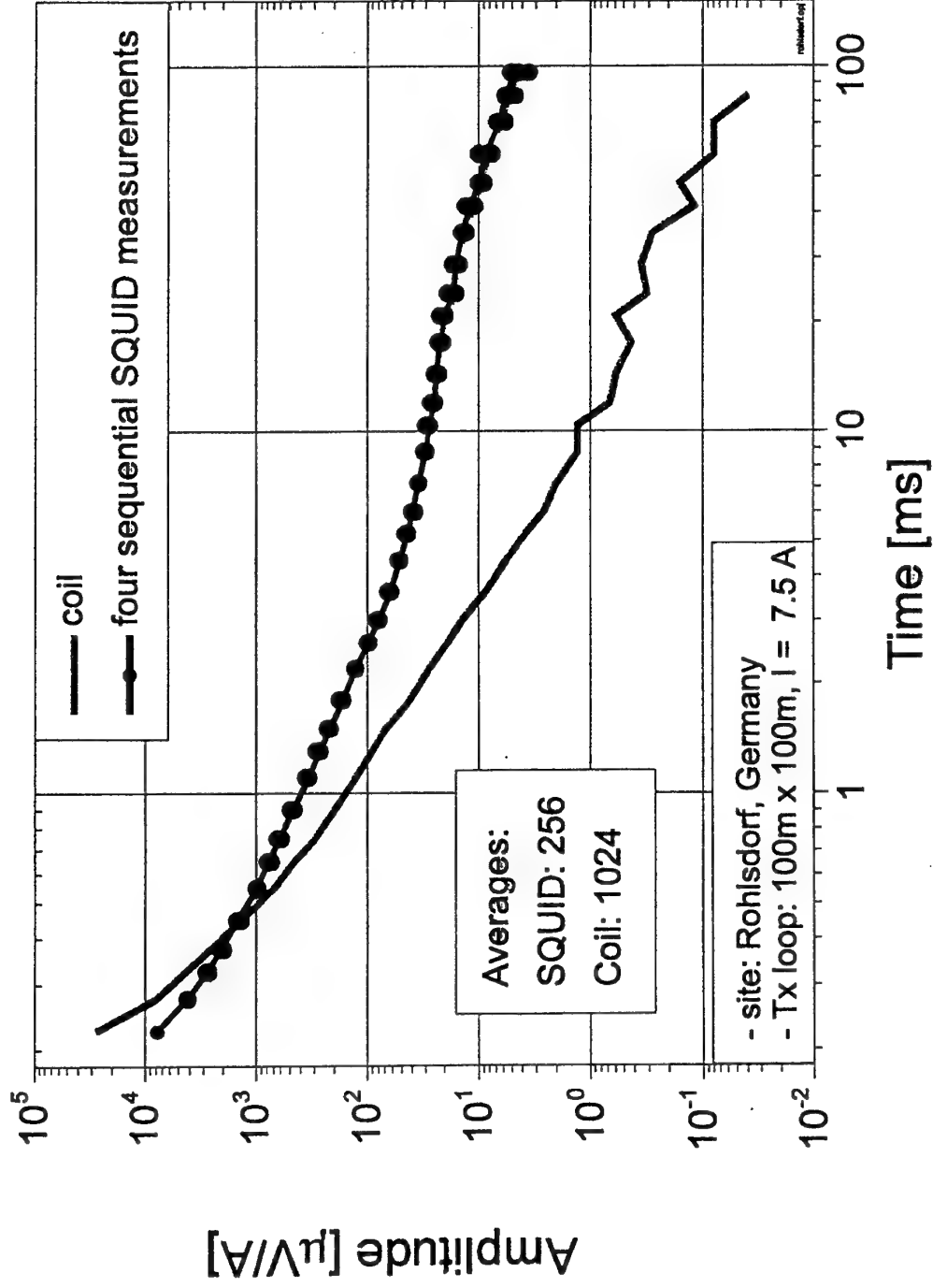


Geophysical Transient Electromagnetics (TEM) Measurements: Advantage HTS rf SQUID over Coil for Late Times



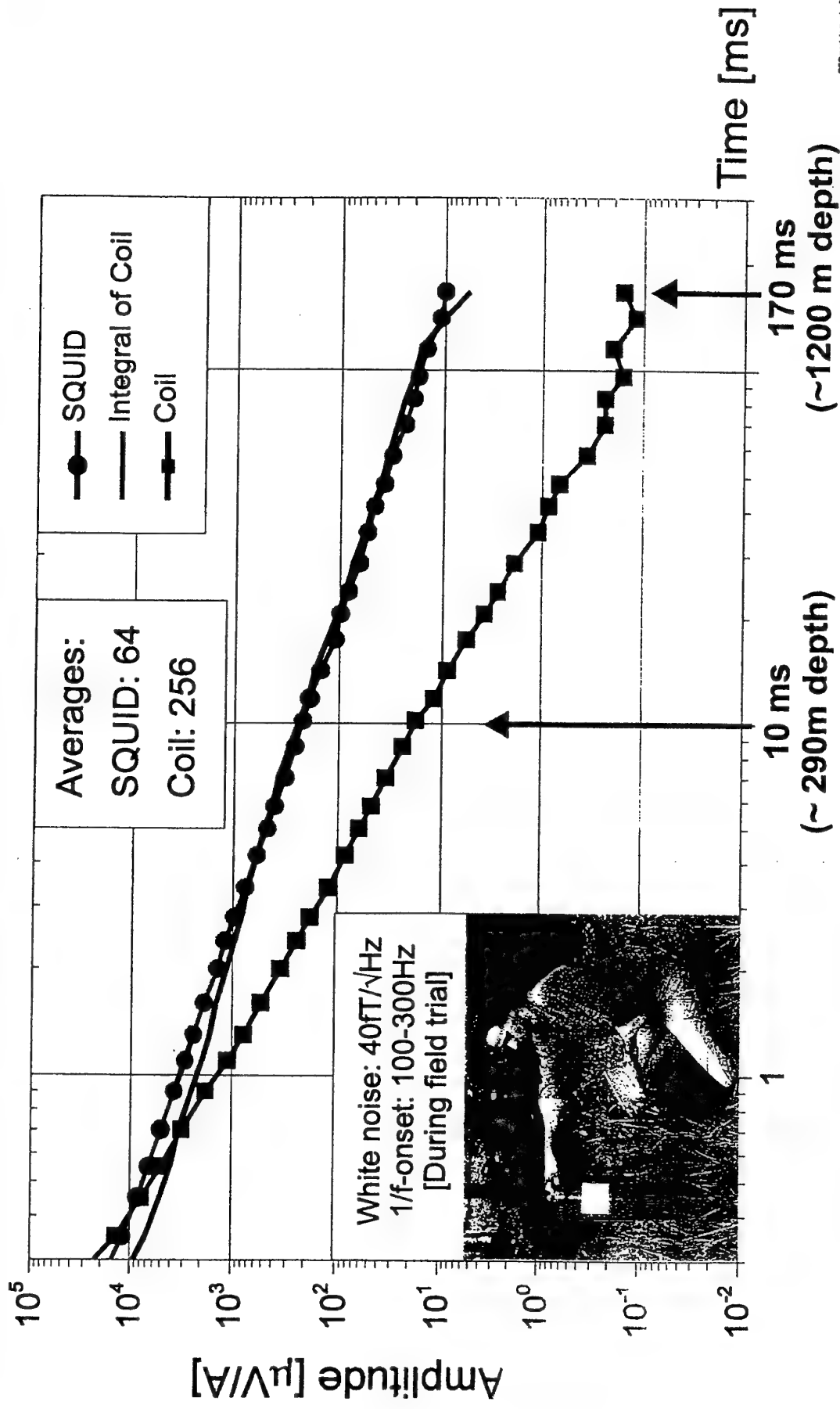
TEM Measurements:

Advantage HTS rf SQUID Over Coil for Late Times



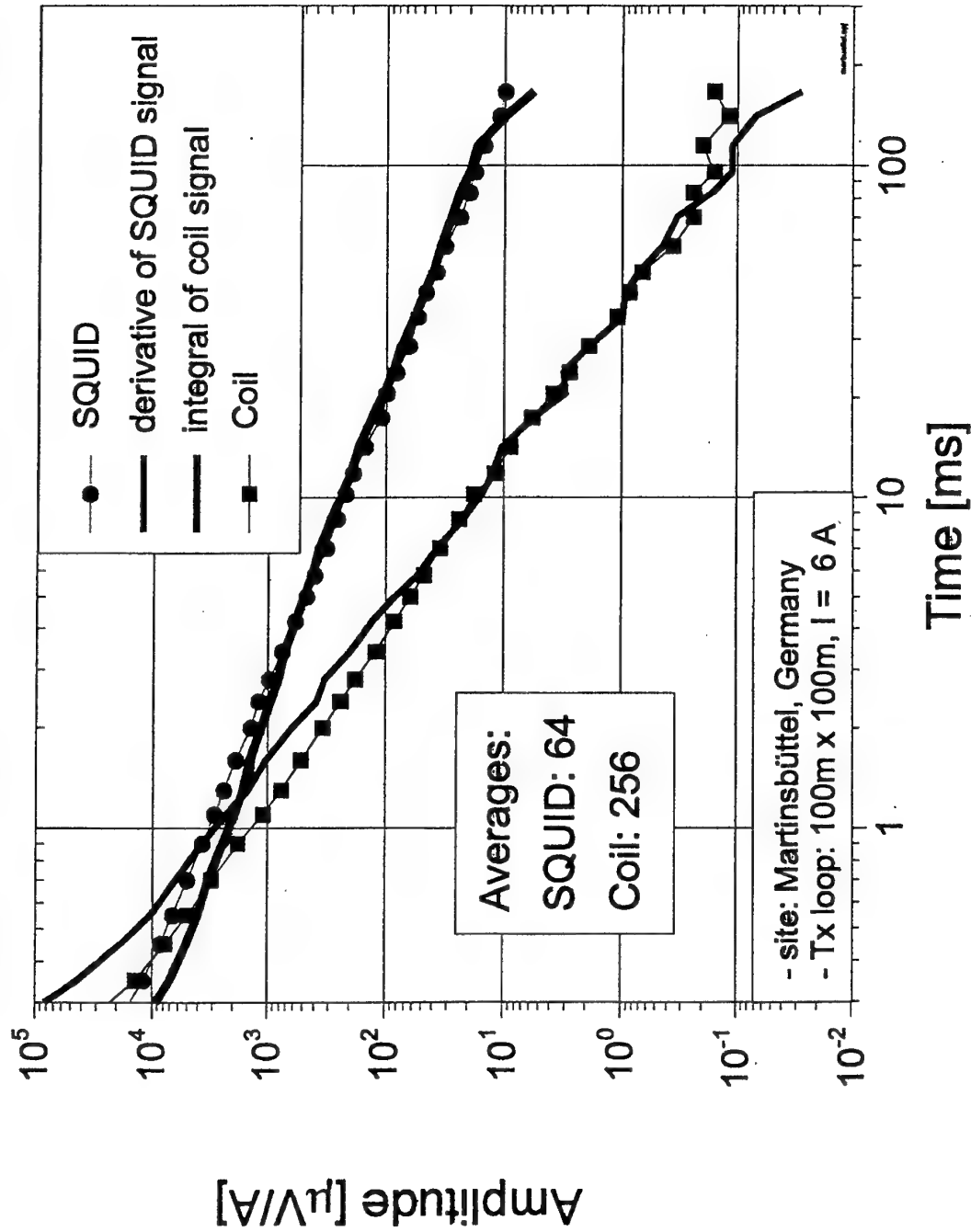
Geophysical Transient Electromagnetics, Measured at Martinsbüttel, Germany

HTS SQUID Provides Better SNR Than Conventional Coil

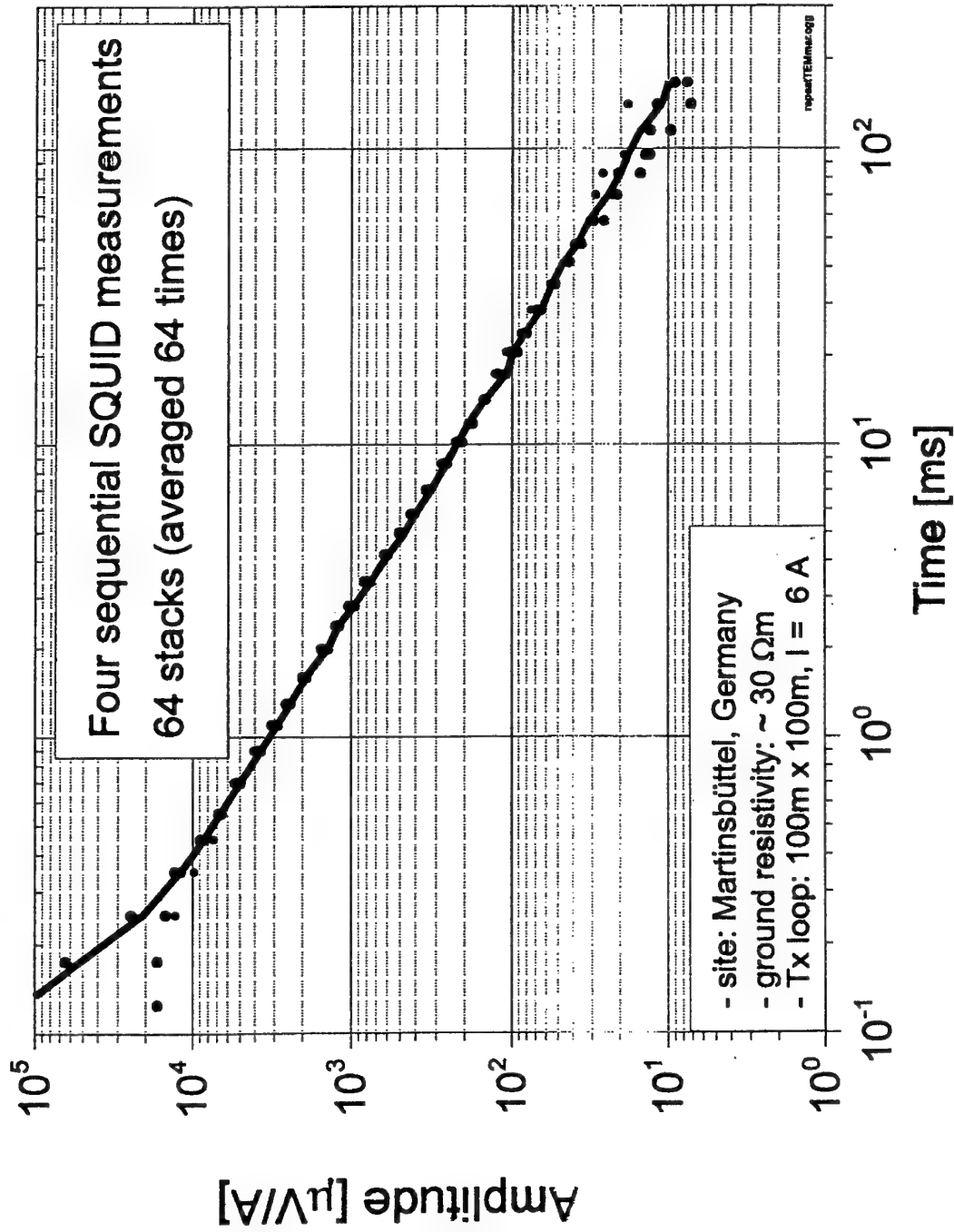


Correlation SQUID - Coil for Late Times

SQUID Provides Better SNR Than Coil

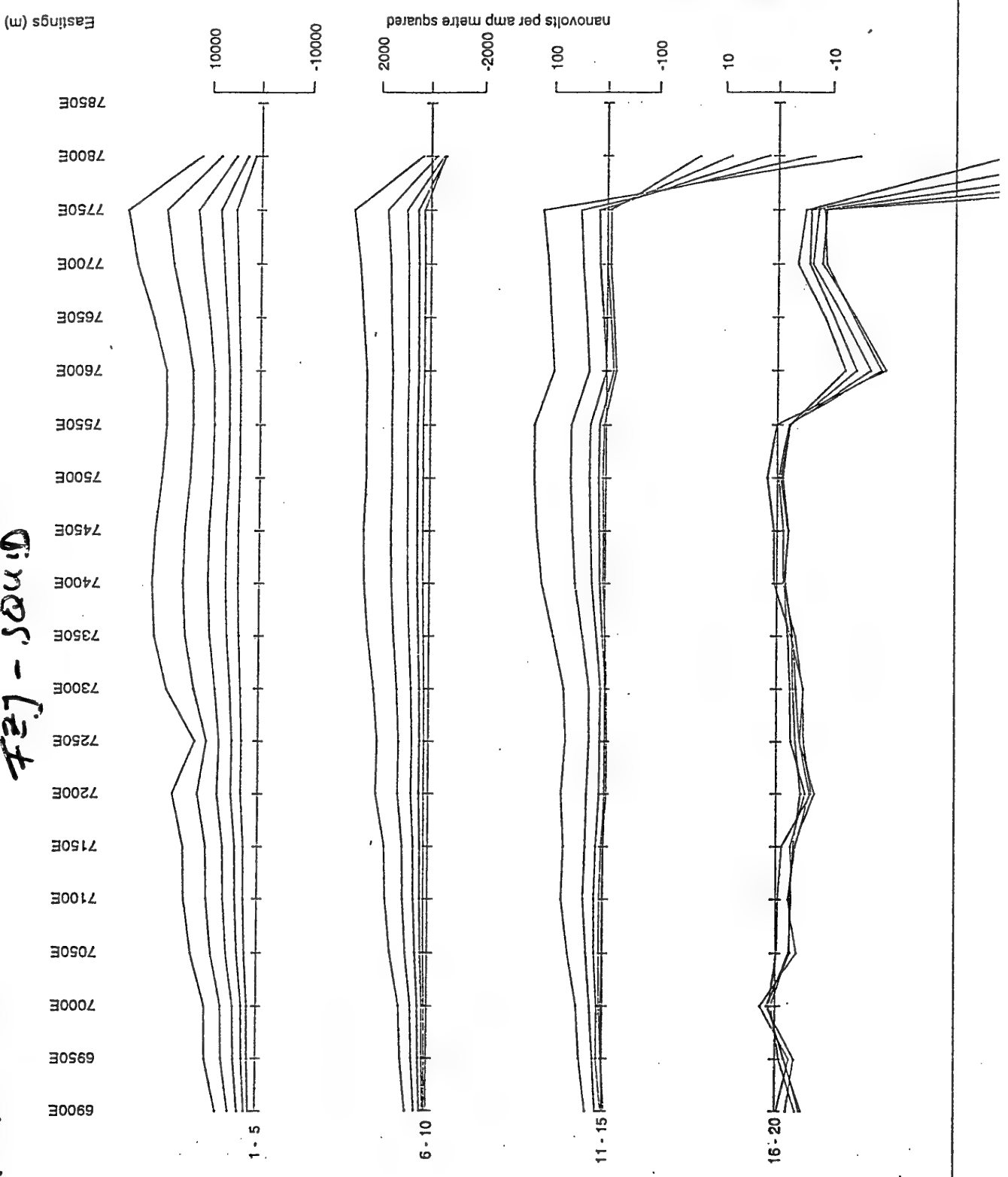


Reproducibility of Geophysical SQUID TEM Measurements



1/EA-MCOTEE
 VERTICAL COMPONENT B(Z)
 #27 - SQUID
 DECOVER 3, 1998

F
 TR/
 ELECTROMOT
 SECT
 TIME DERIVA
 Eloise,
 Queensland
 TX LOOP SIZE
 TX TURN OFF TIME
 FIRST GATE TIME
 CURRENT
 FREQUENCY
 INTEGRATION TIME
 SYNC MODE
 HORIZONTAL SCAL
 SURVEYED BY
 DATE
 CLIENT : G
 PROJECT : T
 AREA : T
 LINE : 8



1/27/98 - 1/28/98
 IPMT - SOUND
 October 24, 1998

F

TR/

ELECTROMOT
SEC

TIME DERIVA

Floise,
 Queensland

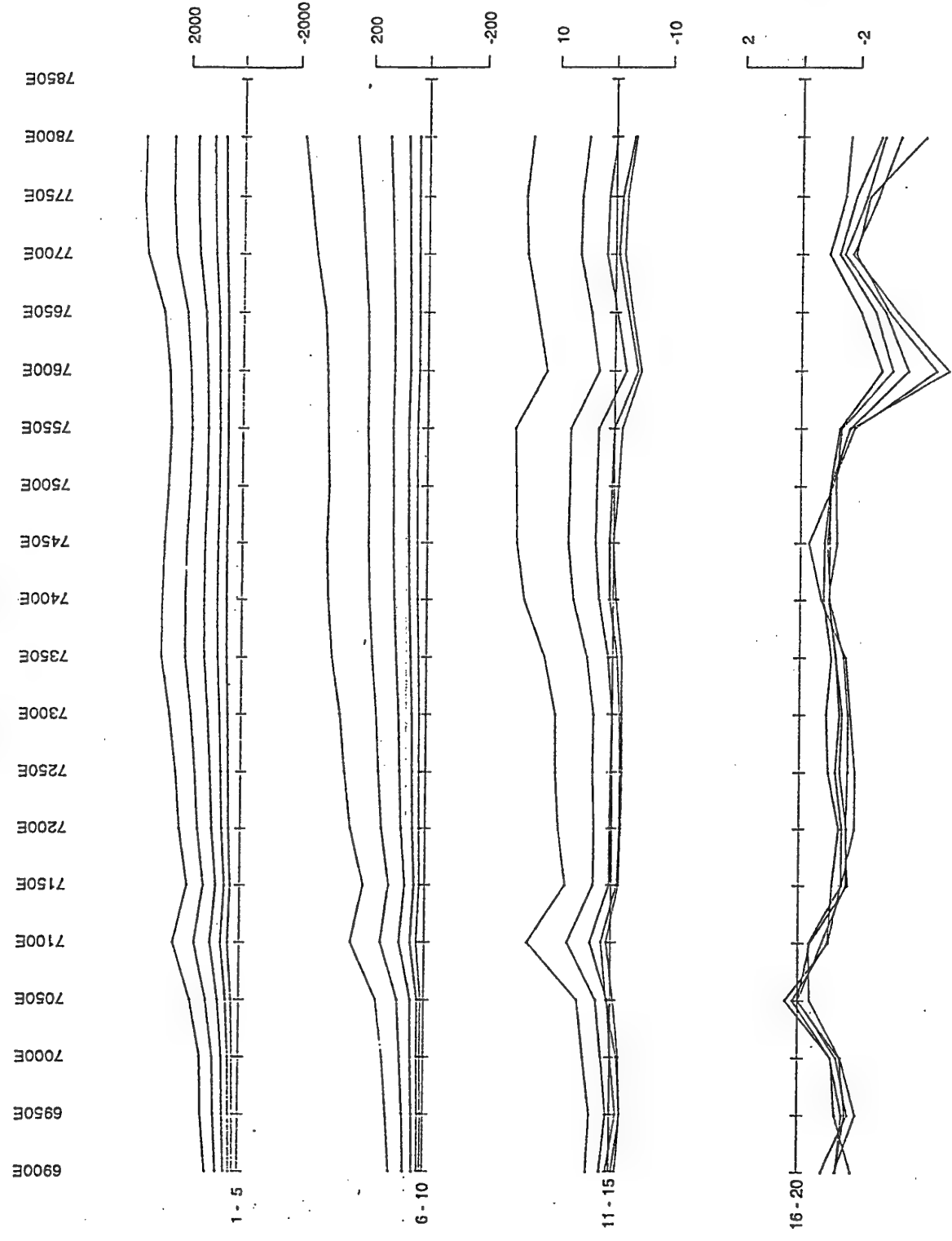
TX LOOP SIZE
 TX TURN OFF TIME
 FIRST GATE TIME
 CURRENT
 FREQUENCY
 INTEGRATION TIME
 SYNC MODE
 HORIZONTAL SCAL
 SURVEYED BY
 DATE



CLIENT : G
 PROJECT : T
 AREA : T
 LINE : 8

Eastings (m)

nanovolts per amp metre squared



15E1-160112

VERTICAL COMPONENT B(Z)
GEOTERREX - COLL

October 24, 1998

Elise,
Greenland

F

TR

ELECTROMOT
SEC

TIME DERIV,

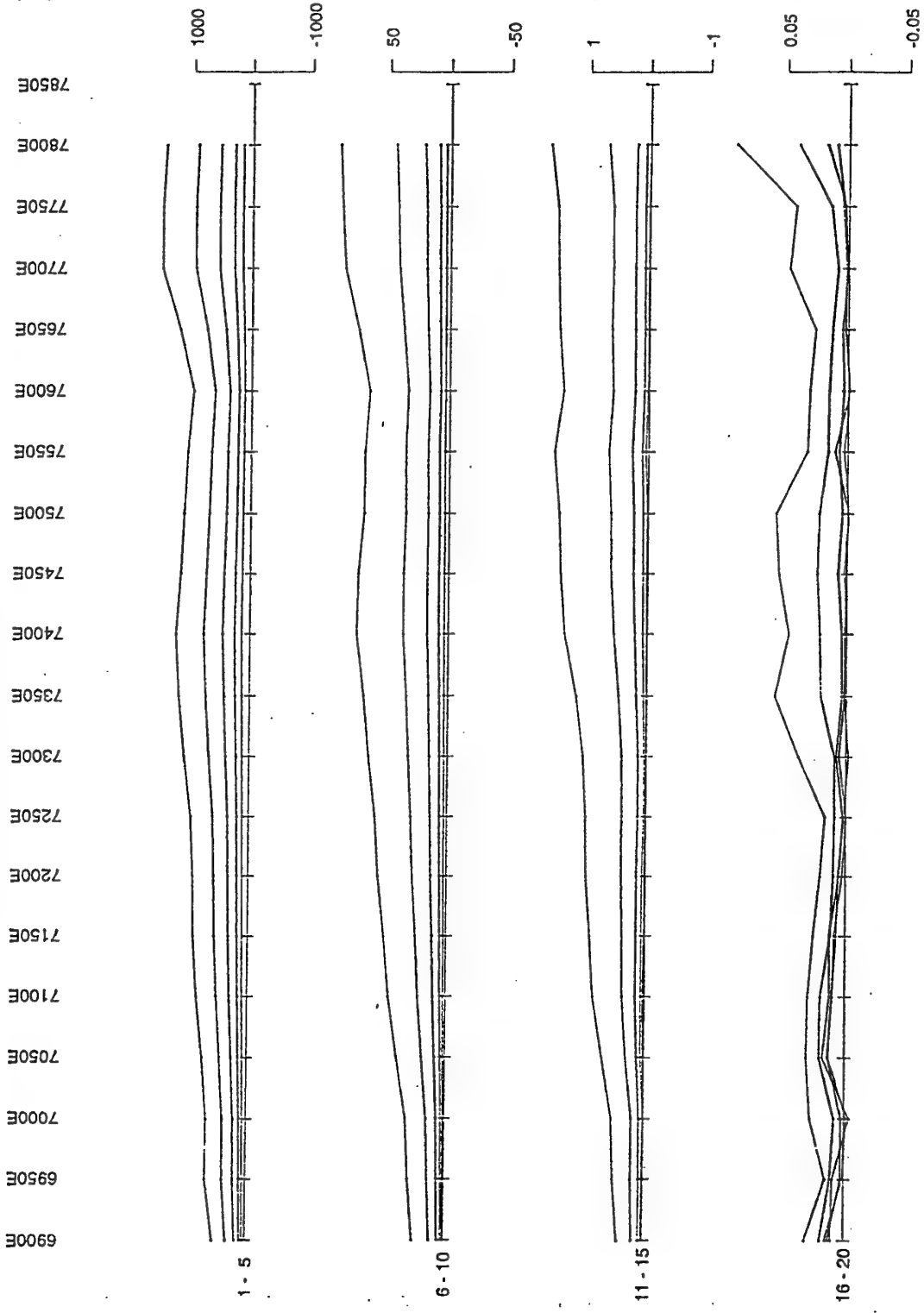
TX LOOP SIZE
TX TURN OFF TIME
FIRST GATE TIME
CURRENT
FREQUENCY
INTEGRATION TIM
SYNC MODE
HORIZONTAL SCA
SURVEYED BY
DATE



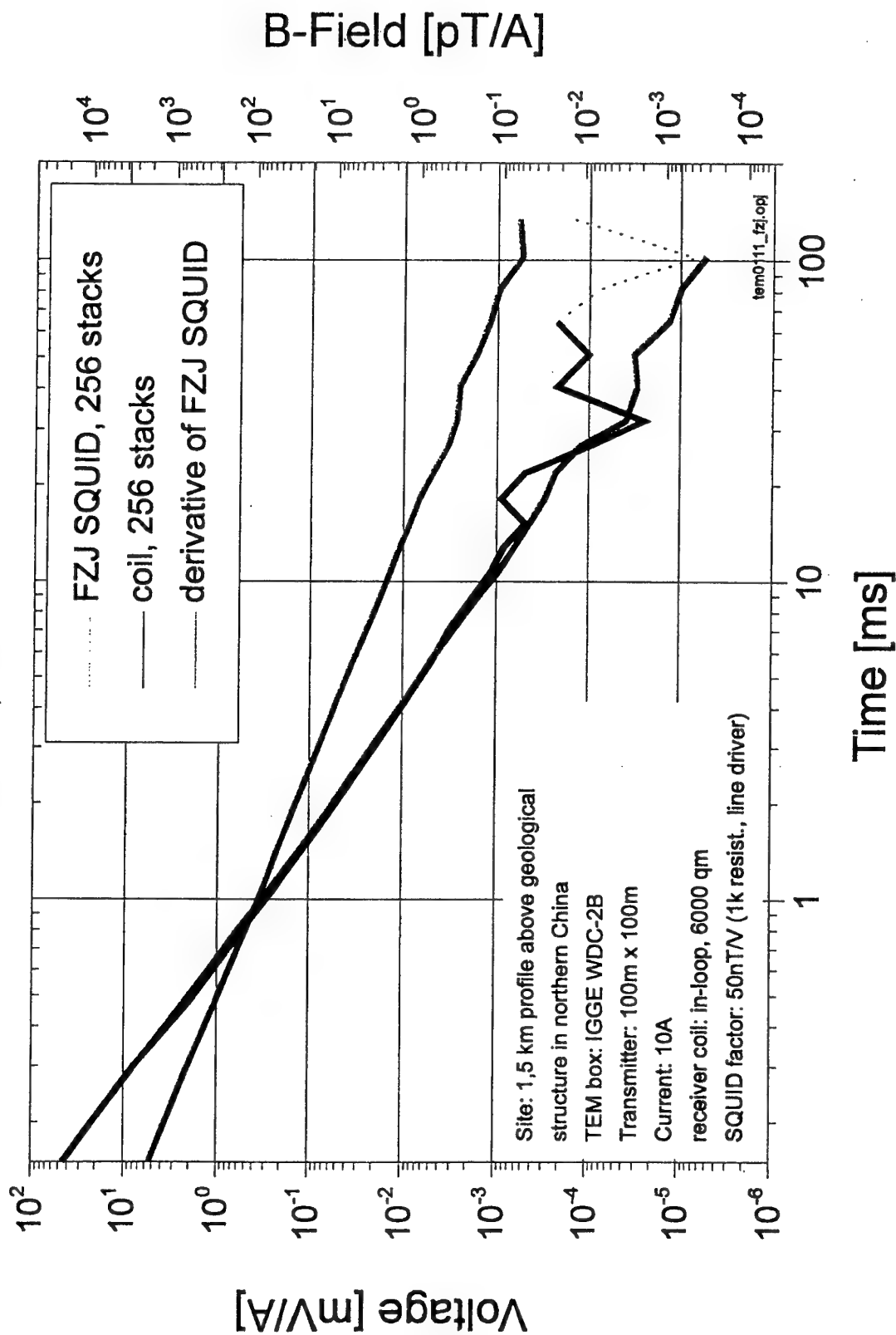
CLIENT :
PROJECT :
AREA :
LINE :

Easting (m)

nanovolts per amp metre squared

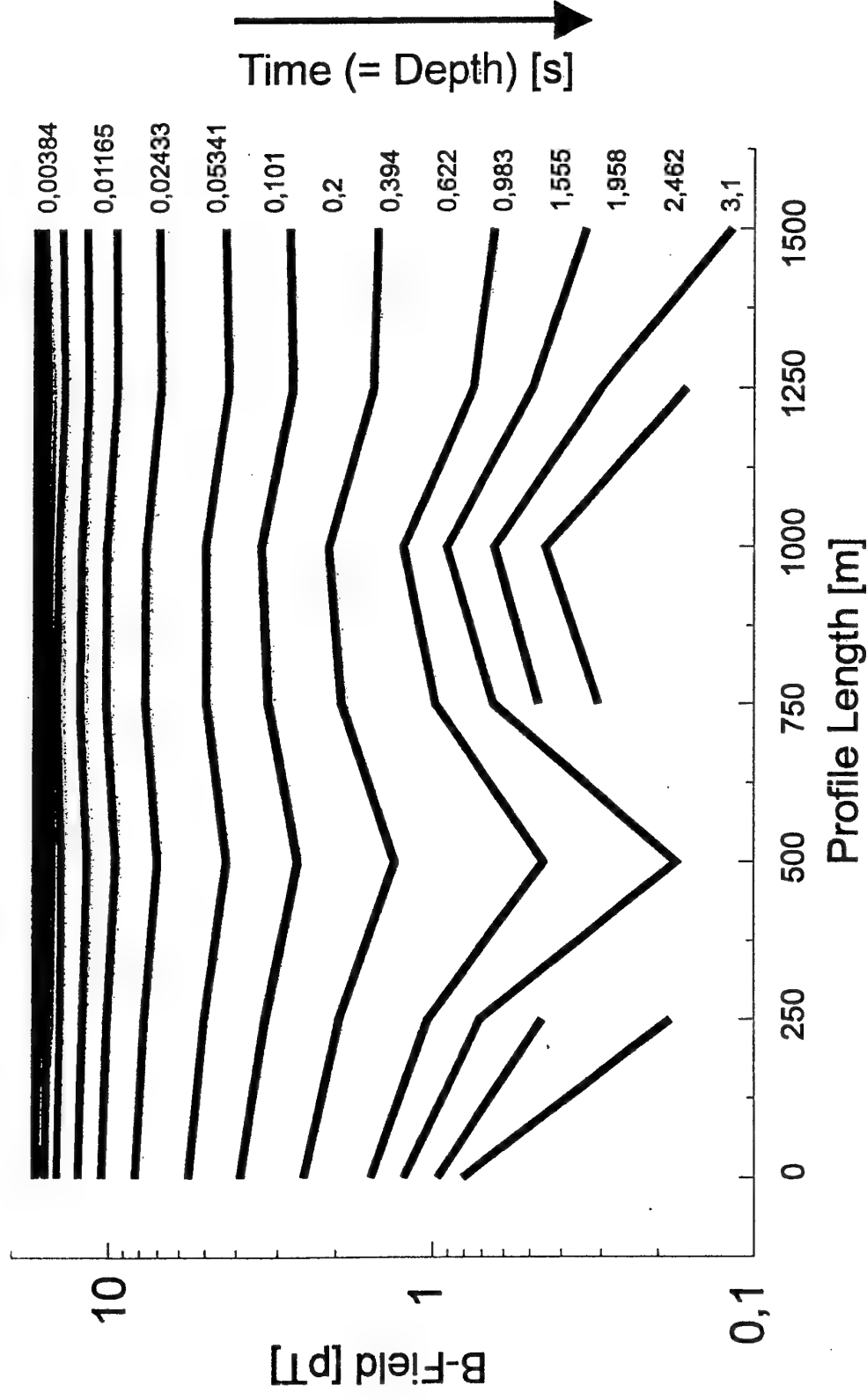


Station 7 of TEM Profile, Northern China, 01.11.98

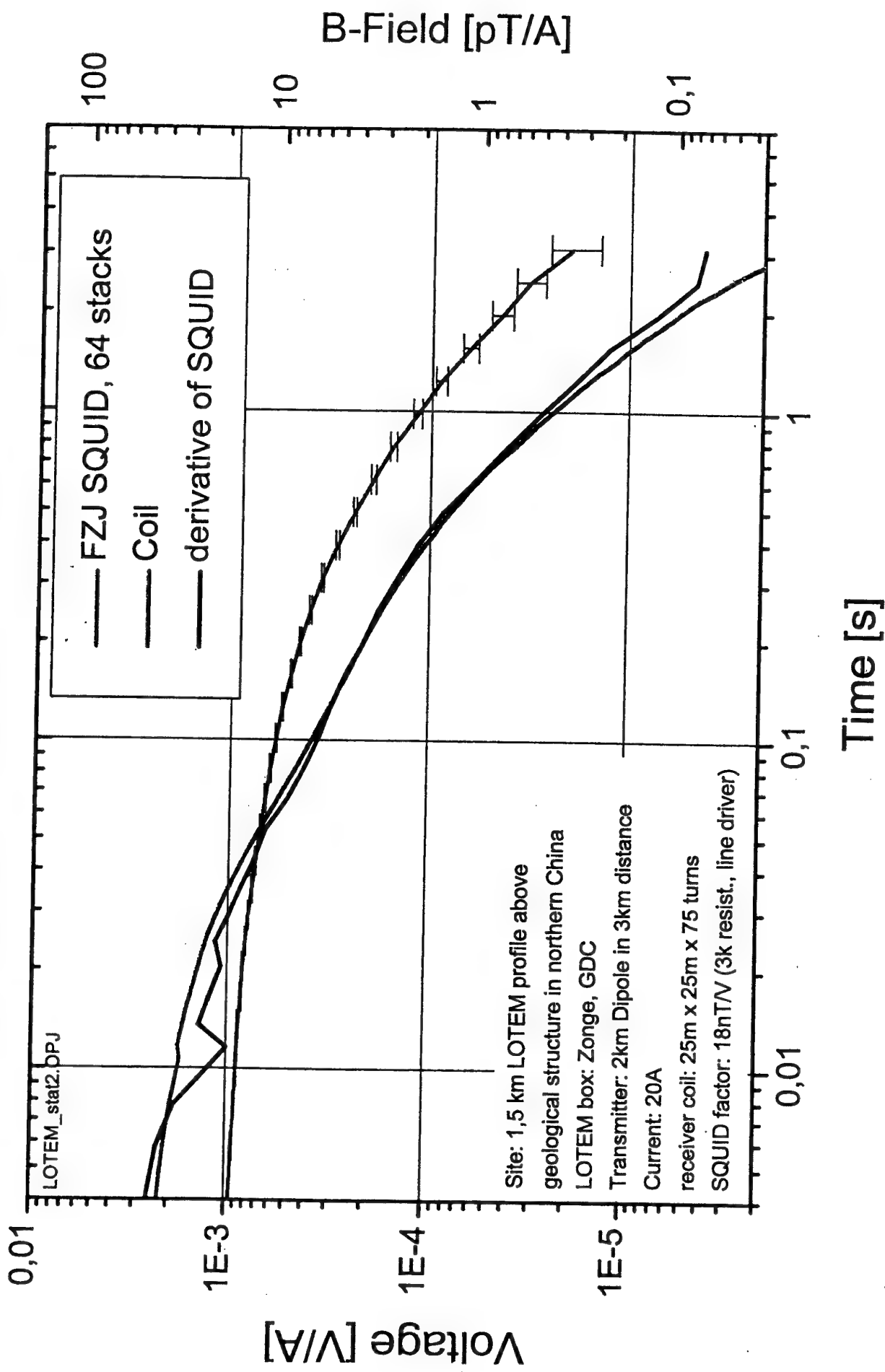


SQUID-LOTEM Profile above

Geological Structure in Northern China



LOTEM, Station 2, Northern China, 03.11.98



Radiomagnetic Sounding

- Above 100 kHz, E_x difficult to measure (sensor dimensions comp. to δ)

- Measure B gradient instead:

$$\text{Curl } \mathbf{B}(\omega) = \mu_0 \mu (1/\rho_a - j\omega\epsilon) \mathbf{E}(\omega)$$

- When $\rho < 100 \Omega\text{cm}$, $f < 1 - 2 \text{ MHz}$, $j\omega\epsilon$ is negligible, and we have:

$$Z_{xy}(\omega) \cong -\rho^*/\Delta z (\Delta B_y(\omega)/B_y(\omega))$$

(with ΔB_y , ρ^* just below surface, $\Delta z \ll \delta$)

- For homogeneous earth ($\rho = \rho^*$):

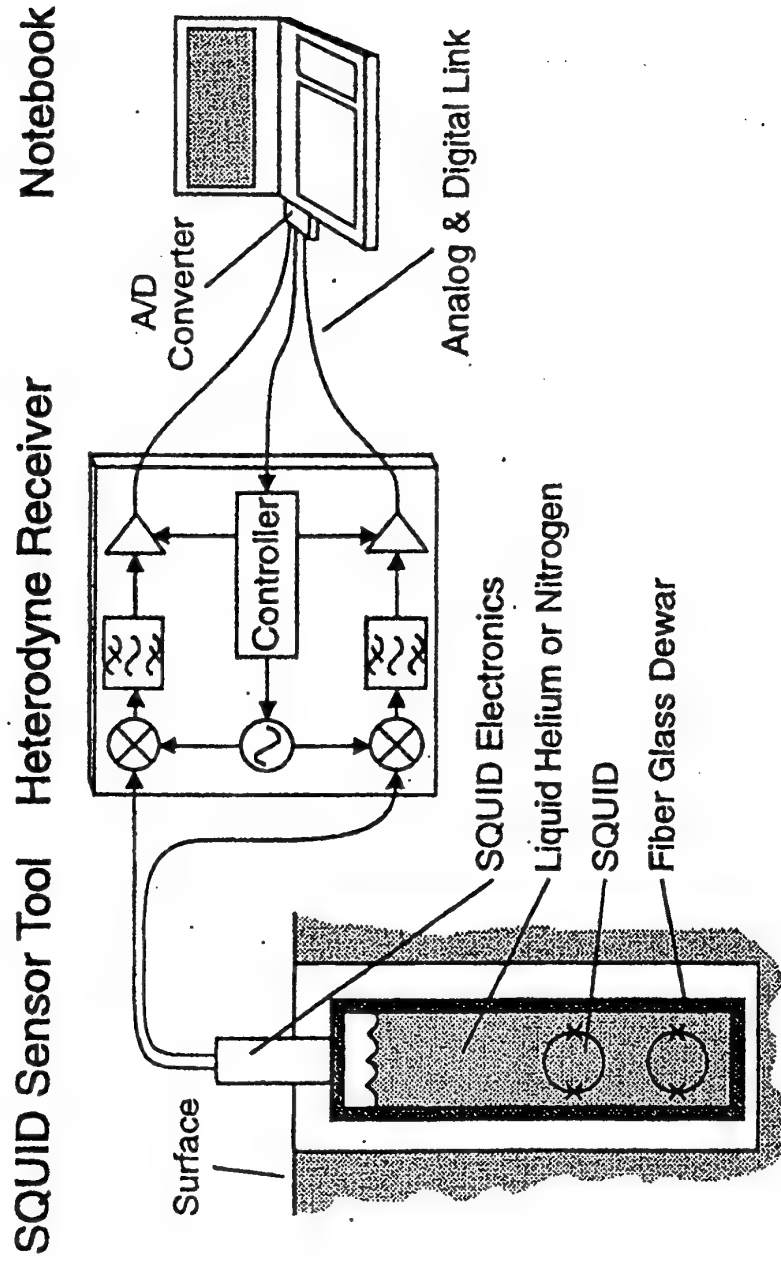
$$|\Delta B_y(\omega)/B_y(\omega)| \cong 2^{1/2} \Delta z / \delta$$

$$\Rightarrow |\Delta B_y| = 8 - 800 \text{ fT}$$

for

$$|B_y| = 1 - 100 \text{ pT}$$

Schematic of LTS RMS (RMT) System



Drung, Radic et al., IEEE Trans. Appl. Supercond. 7, 3283 (1997)



Main Noise Sources in TEM

Determining SNR

1. Intrinsic noise of sensor

2. External disturbances:

- **high frequency [$>20\text{kHz}$ - GHz]**

radio / TV transmitter, mobile phones

⇒ directly affect SQUID's operation

- **low frequency [dc - 20kHz]**

- wind noise (vibrations)
- LF drifts of earth's magnetic field ($\sim 0,3\text{nT/min}$)
- cultural noise ($16^{2/3}\text{Hz}$, 50Hz)
- sferics



2. Intrinsic noise of sensor determining SNR

**Increased LF excess noise
outside magnetic shielding.**

Reasons:

- **Penetration of flux into junction:
suppression and fluctuation of critical current**

possible solution: narrow junction

- **Thermally activated hopping
of flux vortices in YBCO film**

possible solutions:

- high quality YBCO film
- narrow line width of SQUID's structure ($w < \pi \Phi_0 / 4 B_{\text{earth}}$)
- pinning centres (antidots)

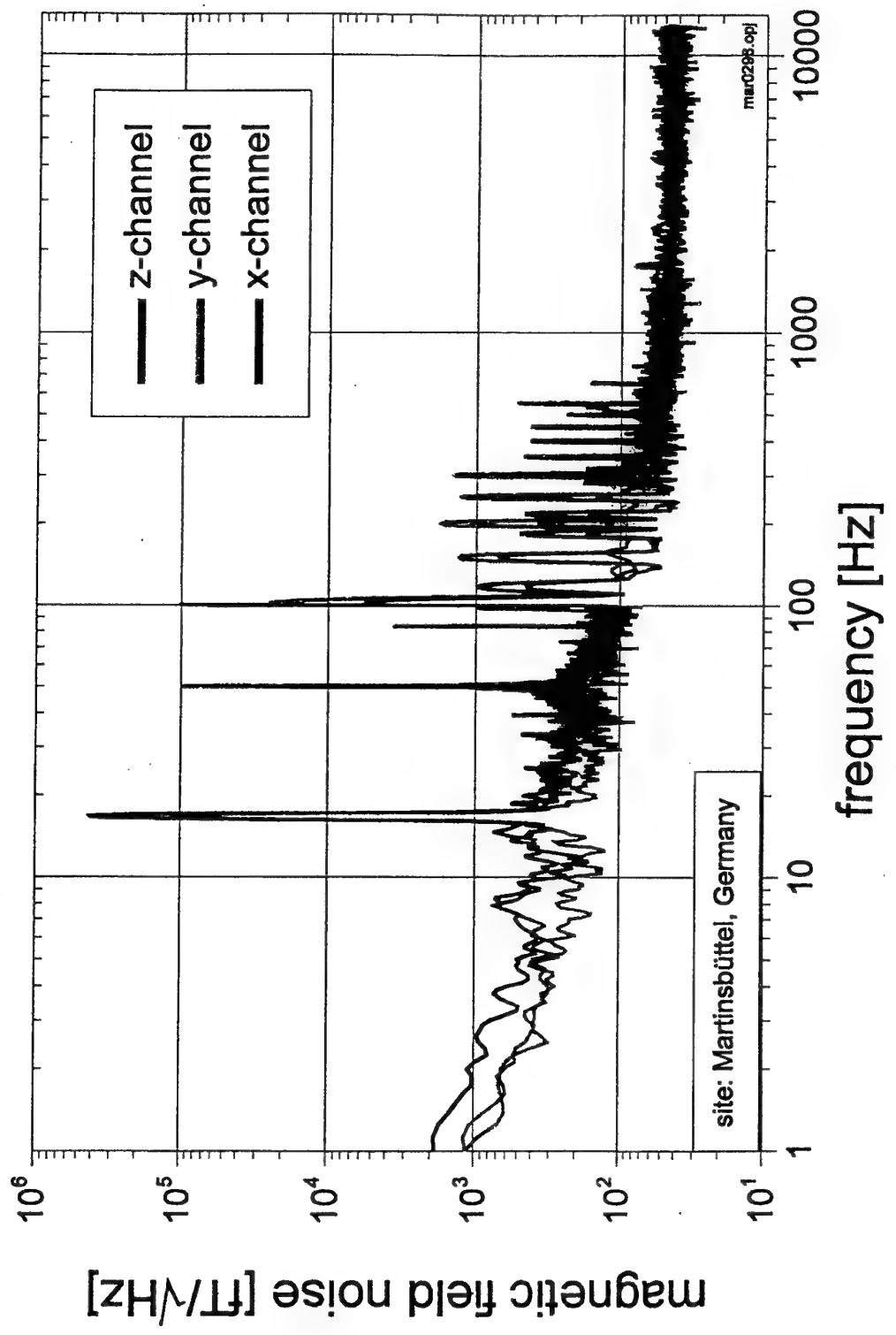
Conclusions

- **The usefulness of SQUID in geophysics was convincingly demonstrated with LTS SQUID, but LHe cooling was prohibitive; LN₂ is not**
- **Recent field tests using HTS SQUID demonstrators have been confirming their potential in TEM and RMS**
- **Further reduction of HTS SQUID low-frequency noise is required, especially for use in magnetotellurics**
- **Also required is ruggedizing & automating of SQUID systems, long cryogen hold time, cryocoolers, borehole-compatible systems**
- **There is potential in HTS SQUID use for prediction of earthquakes and volcano eruptions (and other)**

Outlook

- **Existing interest of industry and users should lead to commercial availability of HTS SQUID systems for TEM in a few years (2000–2005)**
- **New developments in SQUID sensors (Berkeley), may also permit CSAMT systems at a comparable time scale**
- **The RMS using HTS SQUID might find the relatively largest market, after additional development efforts**
- **Novel (electrokinetic) methods, possible only with SQUID, might have a large economic potential in a more distant future**

Typical Magnetic Field Noise of Vector Magnetometer During Field Trial Outside Magnetic Shielding



SQUIDs, Axions, Bugs and Hearts

- SQUIDs – a short review
- The axion detector: a new mode for SQUIDs
- The SQUID microscope: magnetotactic bacteria
- Unshielded magnetocardiography with a high- T_c second-derivative gradiometer

Lyon
16 June 1999

Low-Noise rf Amplifiers Based on dc SQUIDs (LOW- T_c)

Michael Mück and Marc-Olivier André

*Department of Physics
University of California, Berkeley*

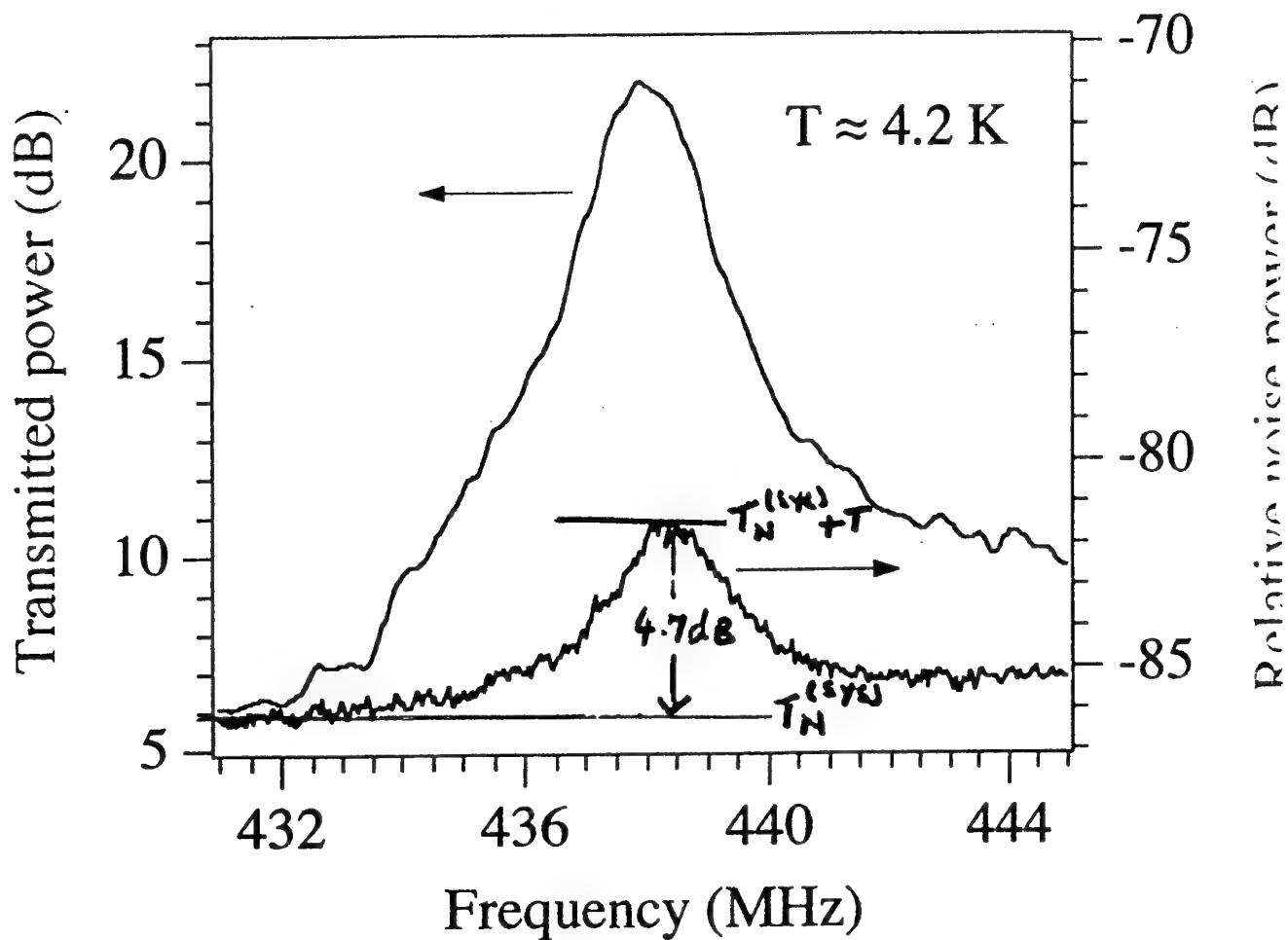
In collaboration with:

Jost Gail and Christoph Heiden

*Institut für Angewandte Physik
Justus-Liebig Universität Gießen, Germany*

XIAOFENG MENG
(VAN DERZEE/MIKROLAB)

LC - Resonator Input



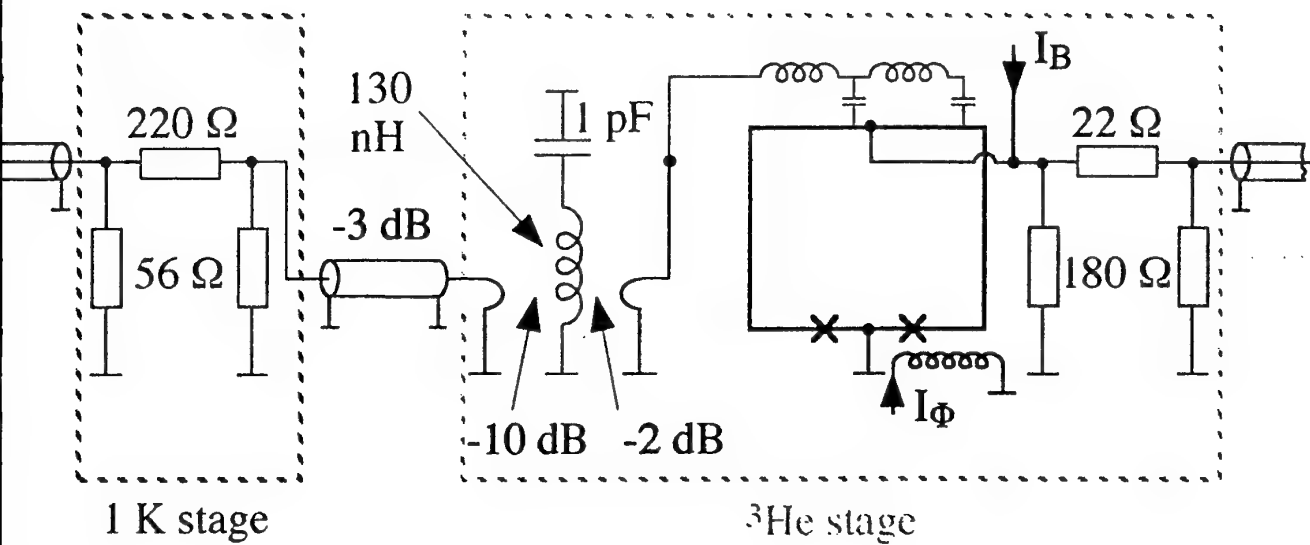
WITH 2dB COUPLING LOSS, PEAK HEIGHT $\approx 6.7 \text{ dB}$

HENCE $10 \log_{10} [T_N^{(SYS)} + T] / T_N^{(SYS)} \approx 6.7$

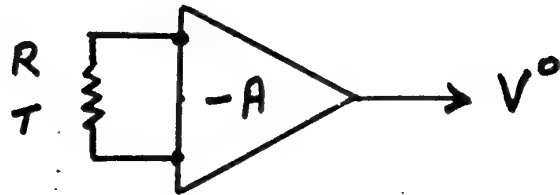
$$T_N^{(SYS)} \approx \underline{1.1 \text{ K}}$$

[MEASURED : $T_N^{(SYS)} = 1.4 \pm 0.18 \text{ K}$]

LC - Resonator Input



NOISE TEMPERATURE



$$S_v^o(f) = A^2 4k_B (T + T_N) R$$

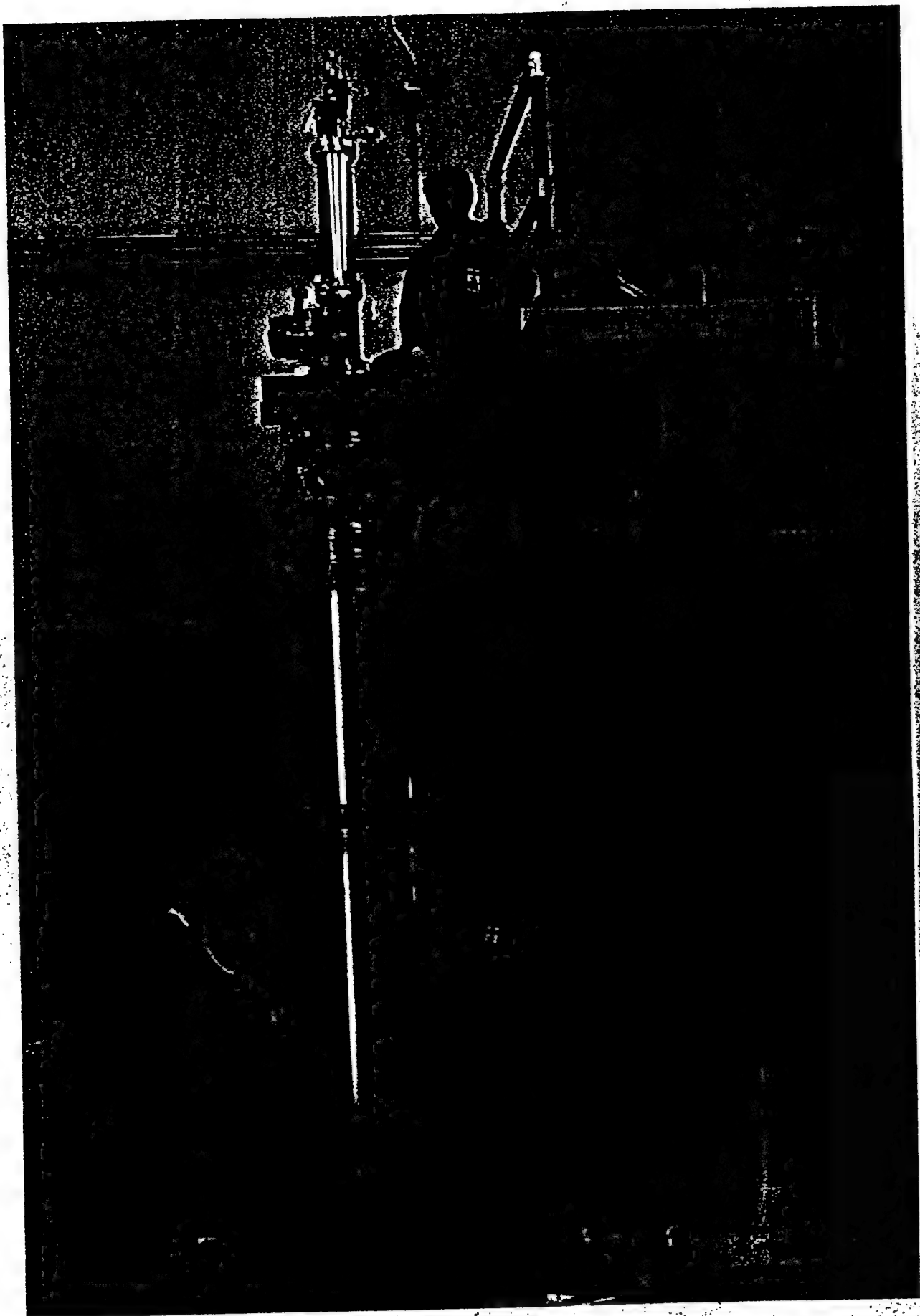
WHERE $T_N = T_N(R)$

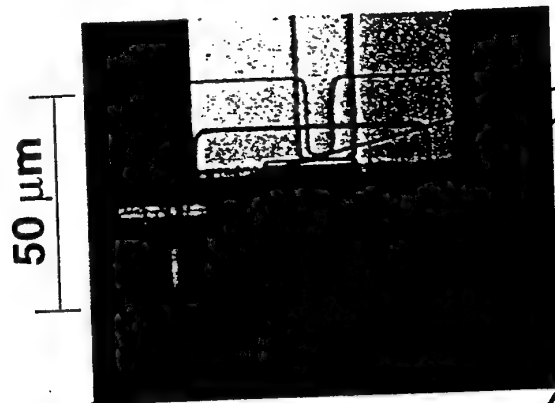
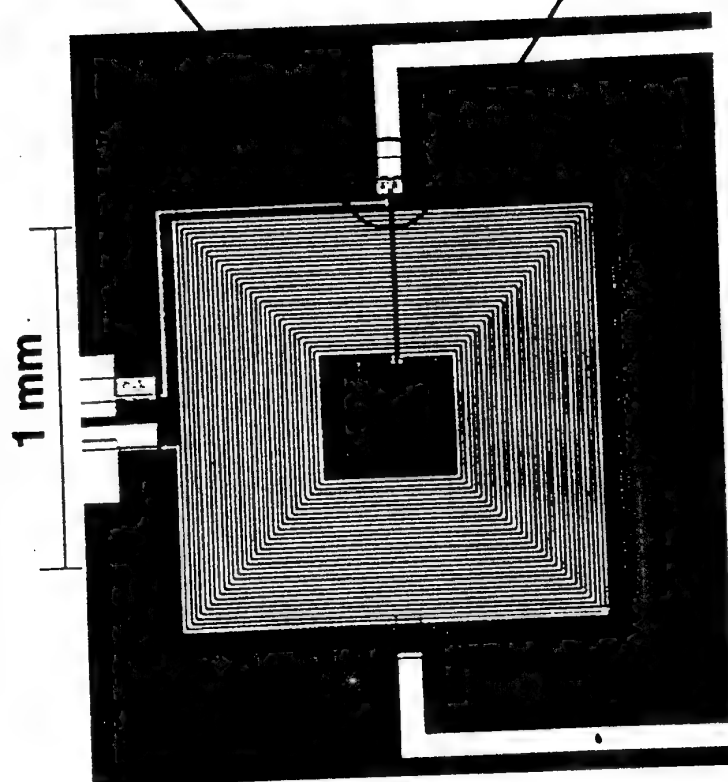
Axions

- The axion is a candidate particle for dark matter
- Energy constrained to $10^{-6} - 10^{-3}$ eV (0.24 - 240 GHz)
- In a magnetic field B_0 an axion can convert into a photon
- In a resonant cavity of volume V and quality factor Q , conversion rate $\propto B_0^2 VQ$

LLNL/MIT Axion Detector

- Cavity 1 m long, 0.5 m diameter : $T_c \approx 1.3$ K
- Frequency range 0.7 - 0.8 GHz
- Output from cavity detected by HEMT amplifier :
 $T_A \approx 1.7$ K
- System noise temperature $T_s = T_c + T_A \approx 3$ K
- Since integration time $\propto T_s$, there is great incentive to run the detector at a lower temperature (say, 0.3 K) provided one has a much quieter amplifier

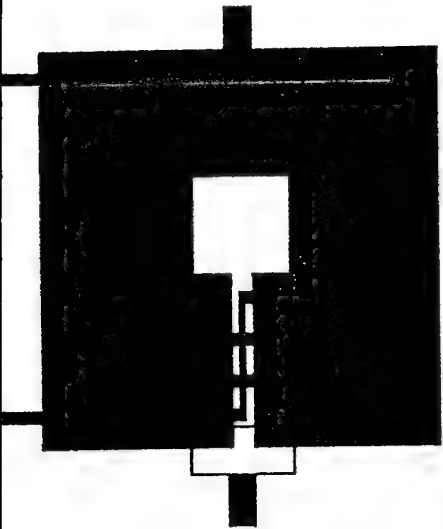




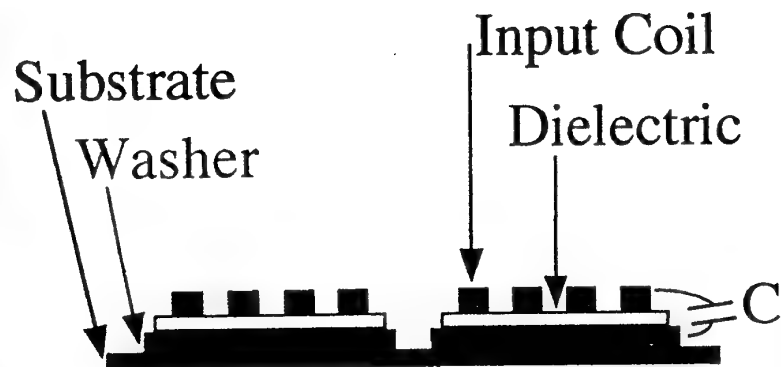
Josephson
junctions

Conventional SQUID design

Top View

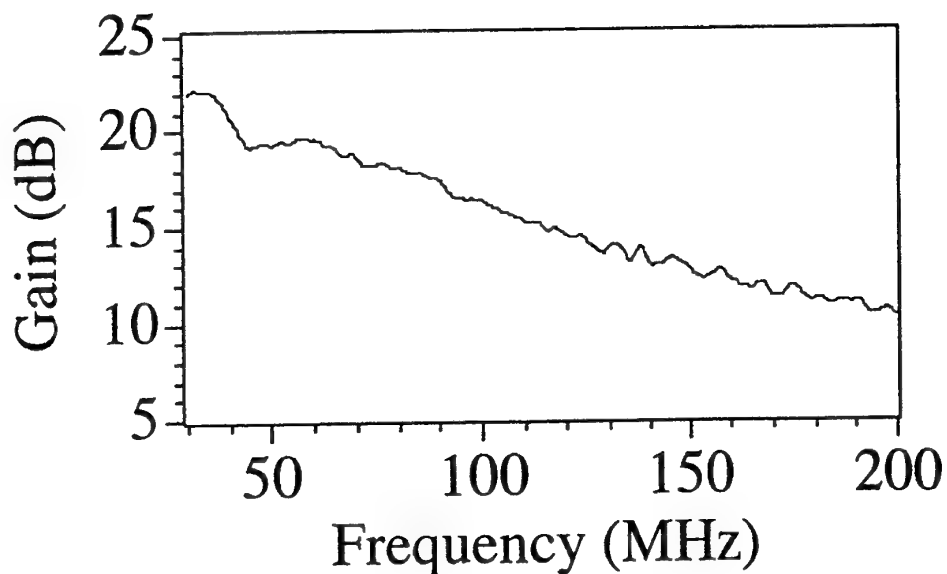


Side View

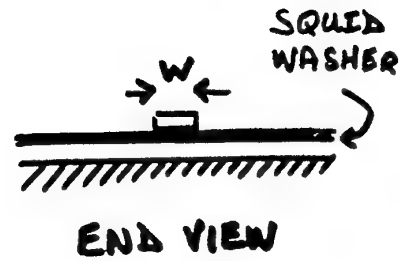
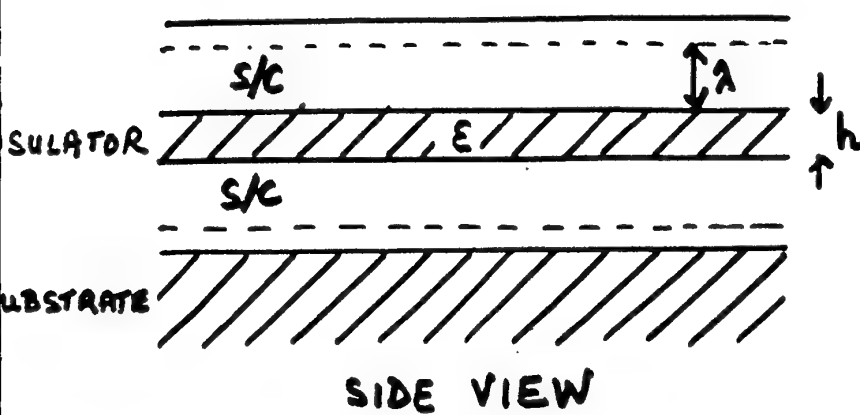


At high frequencies, most of the current flows through the parasitic capacitance rather than the inductance.

This reduces the gain substantially.



MICROSTRIPLINE



$$\begin{aligned} W &\approx 5 \mu\text{m} \\ h &\approx 0.4 \mu\text{m} \\ \epsilon &\approx 9 \\ \lambda &\approx 0.15 \mu\text{m} \end{aligned}$$

NEGLECT FRINGING FIELDS

ASSUME $\lambda < \text{FILM THICKNESS}$

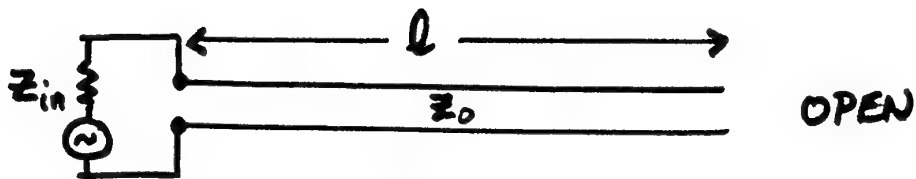
$$\begin{aligned} C/l\text{m} &= \frac{\epsilon \epsilon_0 W}{h} \\ &\approx \underline{1 \text{ nF/m}} \end{aligned}$$

$$\begin{aligned} L/l\text{m} &= \frac{\mu \mu_0 h}{W} \left(1 + \frac{2\lambda}{h} \right) \\ &\approx \underline{175 \text{ nH/m}} \quad \text{INDUCTIVE LOADING} \end{aligned}$$

$$\text{VELOCITY } \bar{c} = \frac{c}{\sqrt{\epsilon} \sqrt{1 + 2\lambda/h}} \approx \underline{0.25c}$$

$$\text{IMPEDANCE } Z_0 = \sqrt{\frac{L}{C}} = \frac{h}{W} \sqrt{\frac{\mu_0}{\epsilon \epsilon_0} \left(1 + \frac{2\lambda}{h} \right)} \approx \underline{13 \Omega}$$

MICROSTRIPLINE RESONANCE

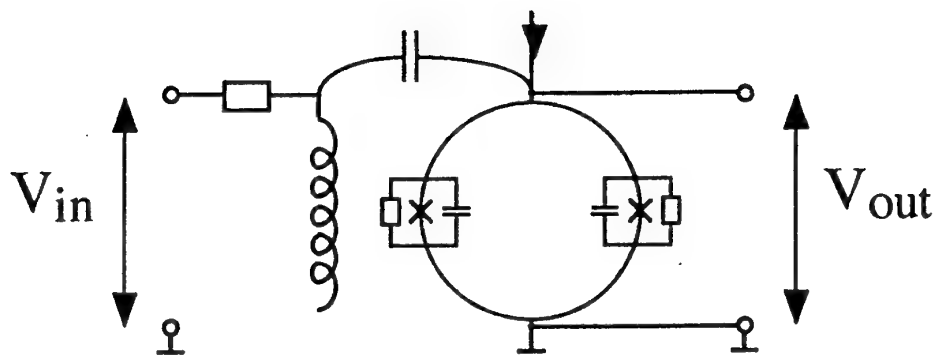


RESONANCE : $\frac{\lambda}{2} = l = \frac{c}{2f}$

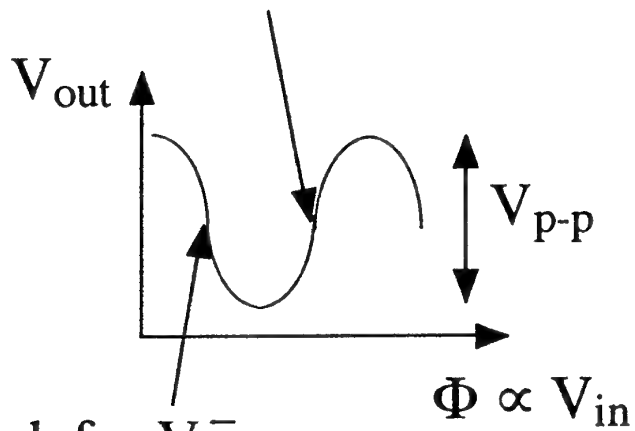
QUALITY FACTOR: $Q = \frac{\pi Z_{in}}{2 Z_0}$

Feedback

Feedback from the output of the SQUID to the input via the capacitance of the microstrip.

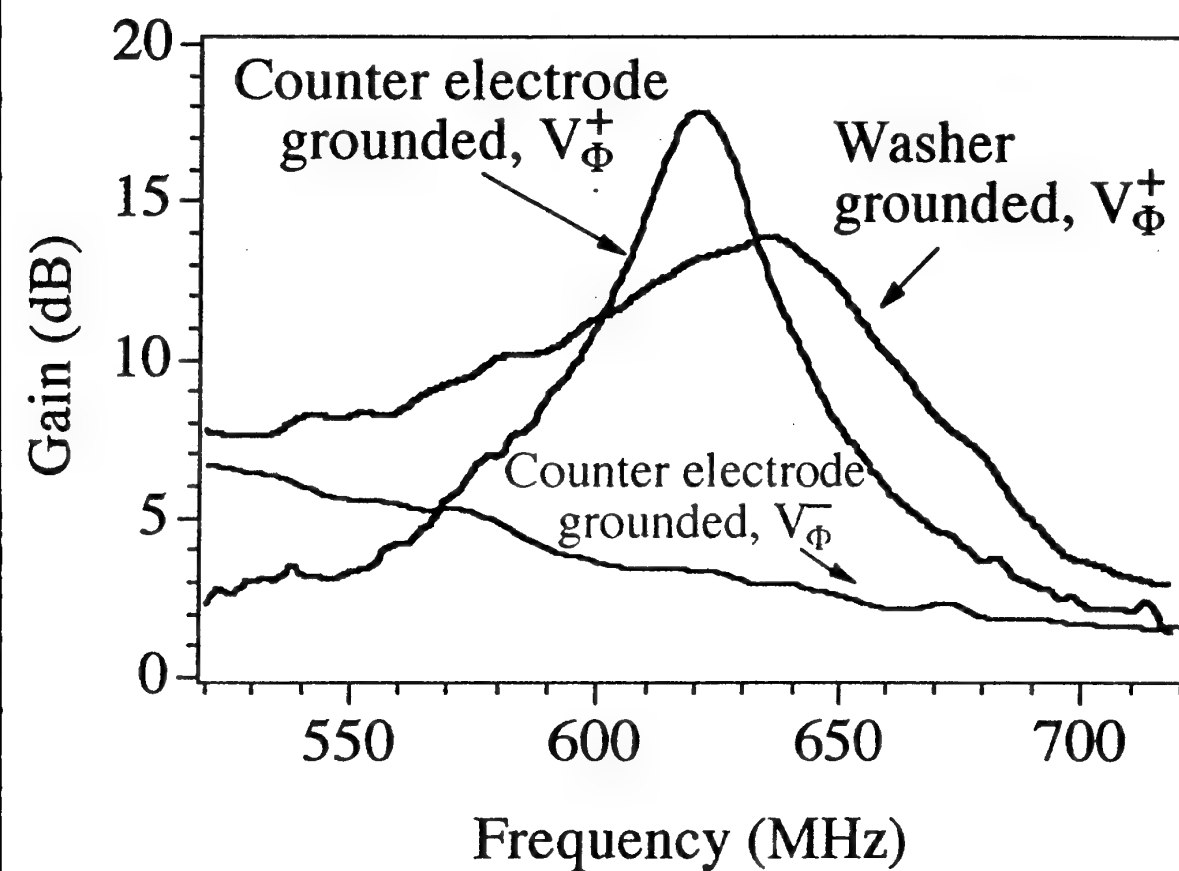
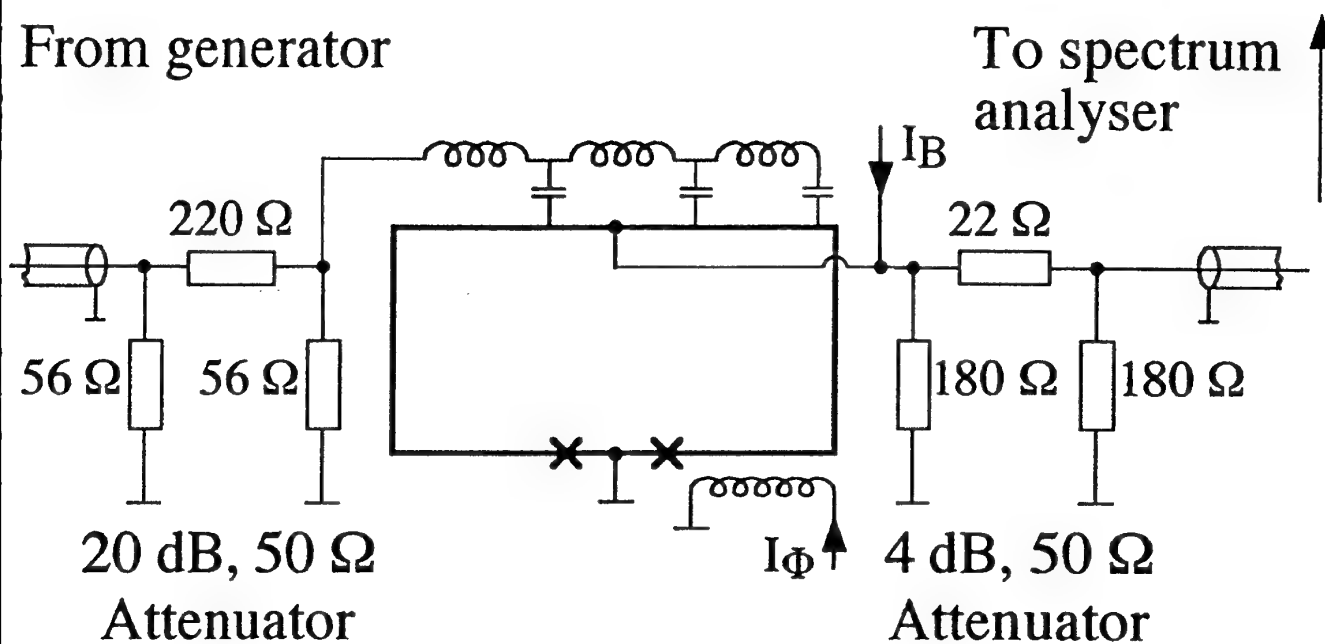


Positive feedback for V_{Φ}^+

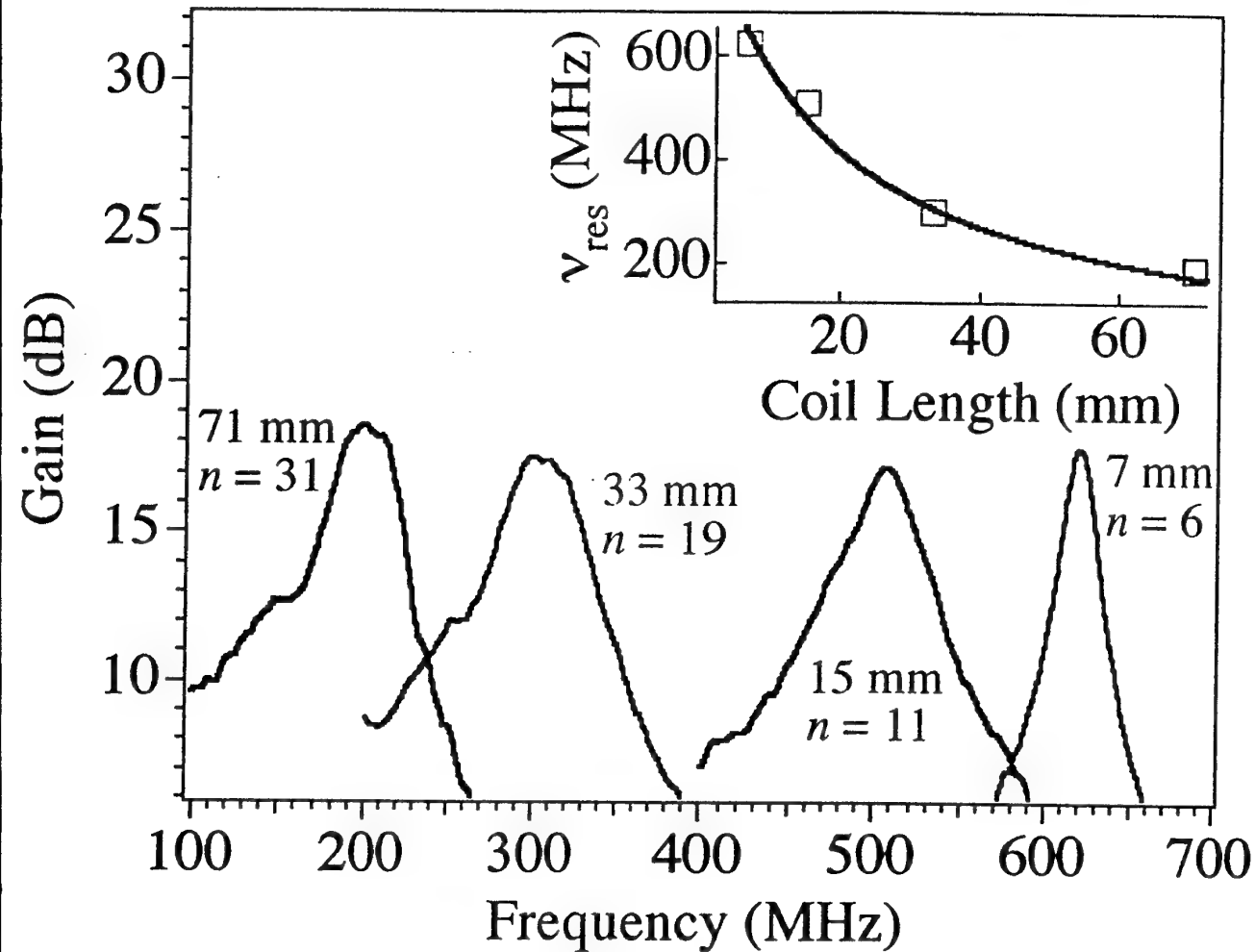


Negative feedback for V_{Φ}^-

Gain Measurements



Gain vs. Coil Length



Fitted line in inset: $\nu_{\text{res}} = \frac{c}{2\sqrt{\epsilon_r \kappa \chi}(l + 16)} \quad (l \text{ in mm})$

- $c = 3 \times 10^8 \text{ m/s}$
- $\epsilon_r (\text{Si}) \approx 9$
- $\kappa \approx 1.75$ arises from inductive loading.
- $\chi \approx 9$ accounts for the SQUID inductance coupled into the microstrip.

RESONANT FREQUENCY

31-TURN COIL : $l = 71\text{mm}$

FUNDAMENTAL RESONANCE $\frac{\bar{c}}{2l} \approx 530\text{MHz}$ FOR $\bar{c} = 0.25c$

MEASURED RESONANT FREQUENCY $\approx \underline{200\text{MHz}}$

SCALE MODEL 195:1

31-TURN COPPER COIL ON ONE SIDE OF PC BOARD.

HOLE & SLIT ON THE REVERSE SIDE.

MEASURE RESONANT FREQUENCY OF COIL.

- HOLE & SLIT COVERED WITH CU SHEET :

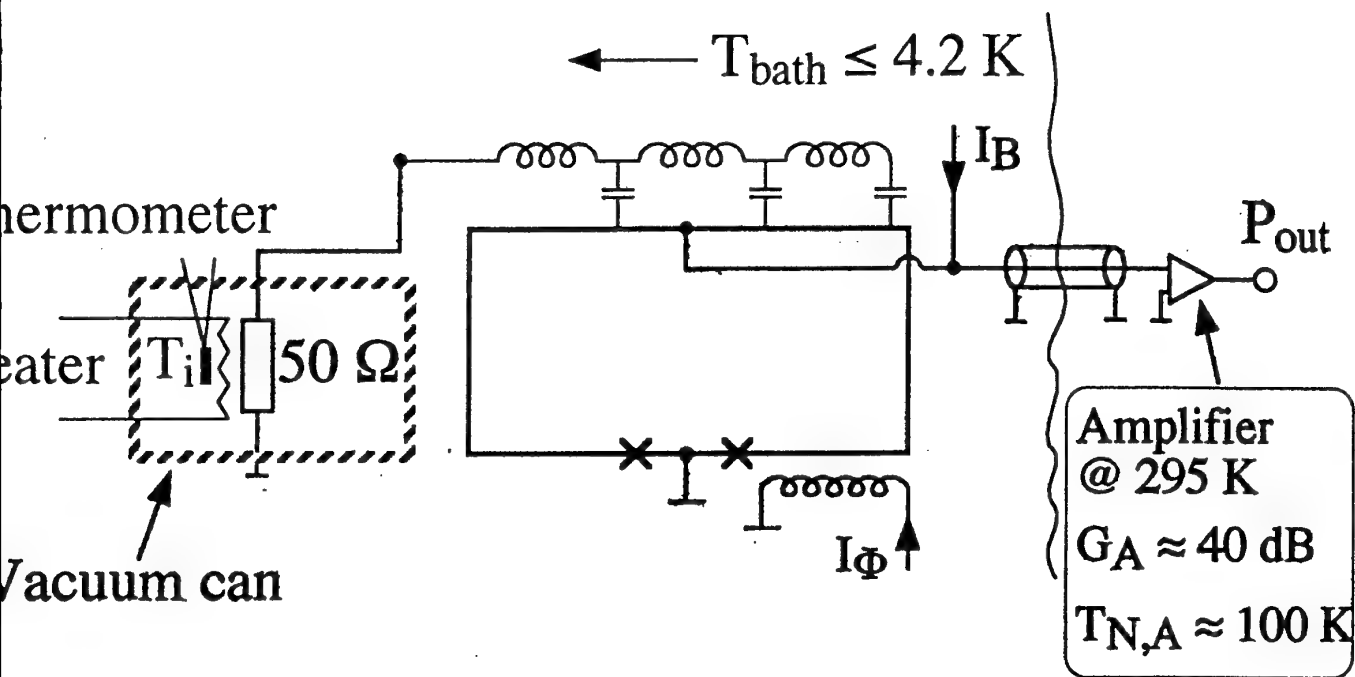
RESONANCE AT EXPECTED FREQUENCY

- HOLE & SLIT UNCOVERED :

RESONANT FREQUENCY DROPS BY FACTOR ~ 3

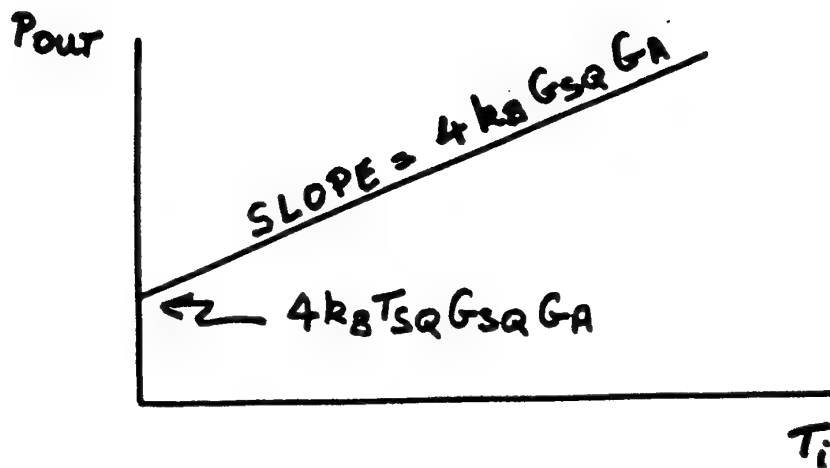
- HENCE IT APPEARS THAT INDUCTANCE COUPLED INTO THE COIL SLOWS THE WAVE VELOCITY.

Noise Temperature Measurements

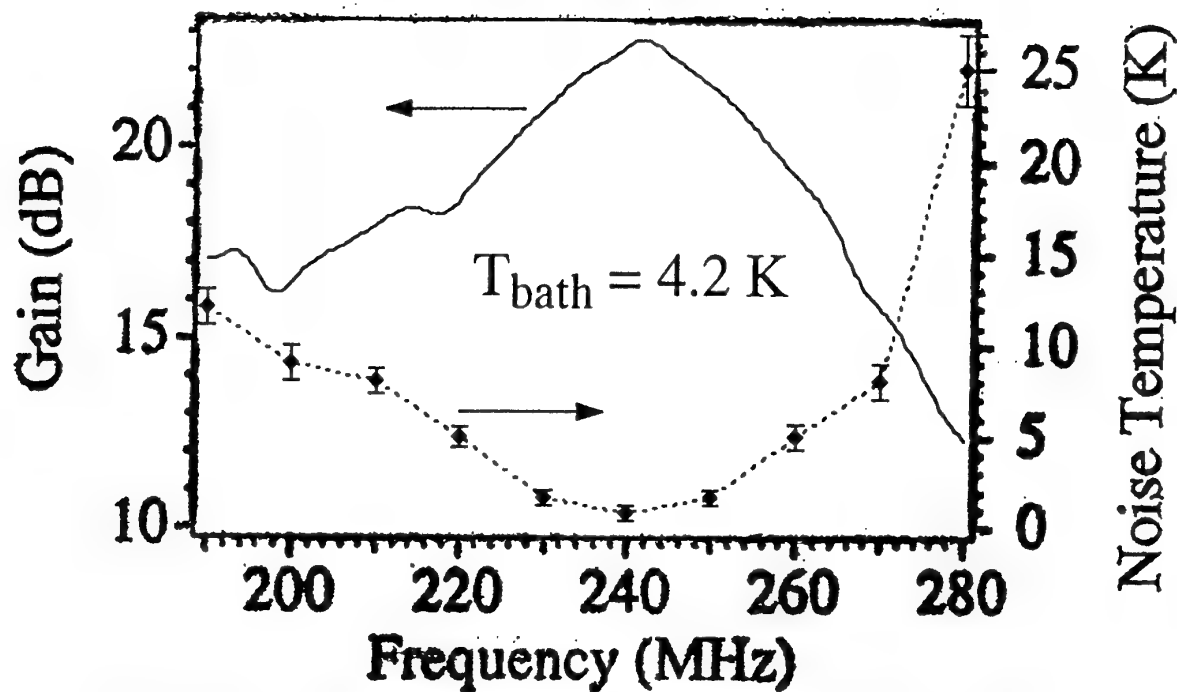


IF WE NEGLECT THE NOISE OF THE POSTAMPLIFIER

$$P_{\text{out}} = 4k_B (T_i + T_{SQ}) G_{SQ} G_A$$



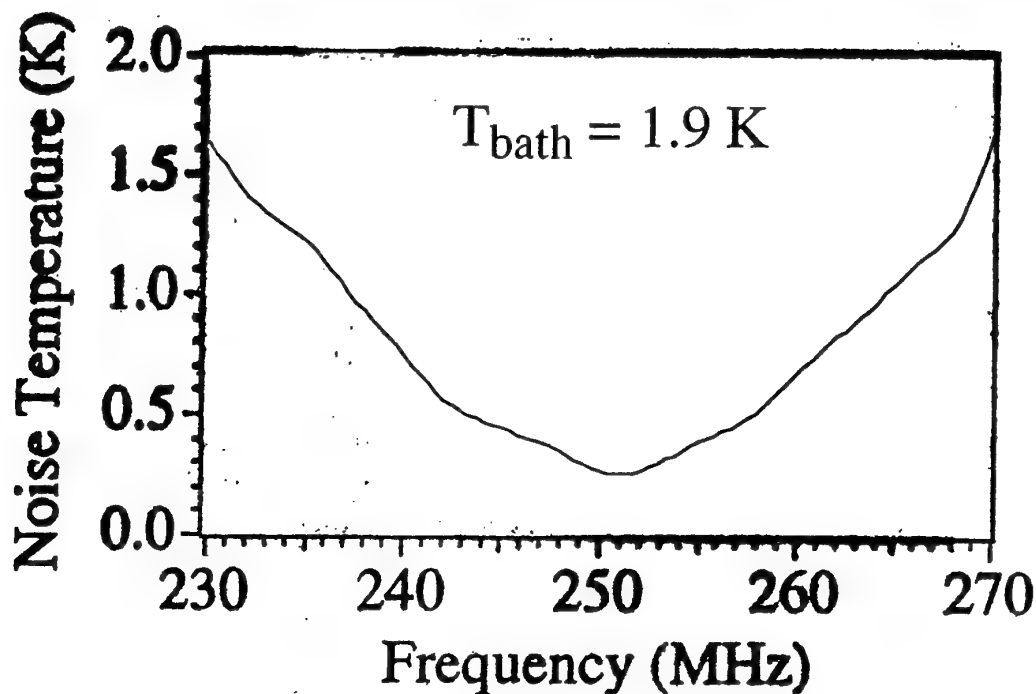
Results



Noise temperature of the 295 K post-amplifier: $\sim 100 \text{ K}$.

SQUID Gain ≈ 200 \longleftrightarrow 0.5 K at SQUID input.

Using a cold **HEMT post-amp** ($G_A \approx 17 \text{ dB}$, $T_{N,A} \approx 8 \text{ K}$)



PERFORMANCE OF MICROSTRIP SOLID AMPLIFIERS

WITH COOLED HEMT POSTAMPLIFIER

<u>FREQUENCY</u> (MHZ)	<u>I</u>	<u>GAIN</u>	<u>T_N^(SQ)</u>	<u>T_N^(SQ)</u>
90	4.2	24	0.90 ± 0.12	0.86 ± 0.12
90	0.4	24.5	0.10 ± 0.02	0.06 ± 0.02
438	4.2	20	1.40 ± 0.18	1.02 ± 0.19
438	0.5	20	0.50 ± 0.07	0.12 ± 0.10

NOTE: AT 438 MHZ, $T_N^{eq} = hf/k_B \ln 2 \approx \underline{0.03K}$

RESONANT FREQUENCY

31-TURN COIL : $\ell = 71\text{mm}$

FUNDAMENTAL RESONANCE $\frac{\bar{c}}{2\ell} \approx 530\text{MHz}$ FOR $\bar{c} = 0.25c$

MEASURED RESONANT FREQUENCY $\approx \underline{200\text{MHz}}$

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MEASURE RESONANT FREQUENCY OF COIL.

- HOLE & SLIT COVERED WITH CU SHEET :

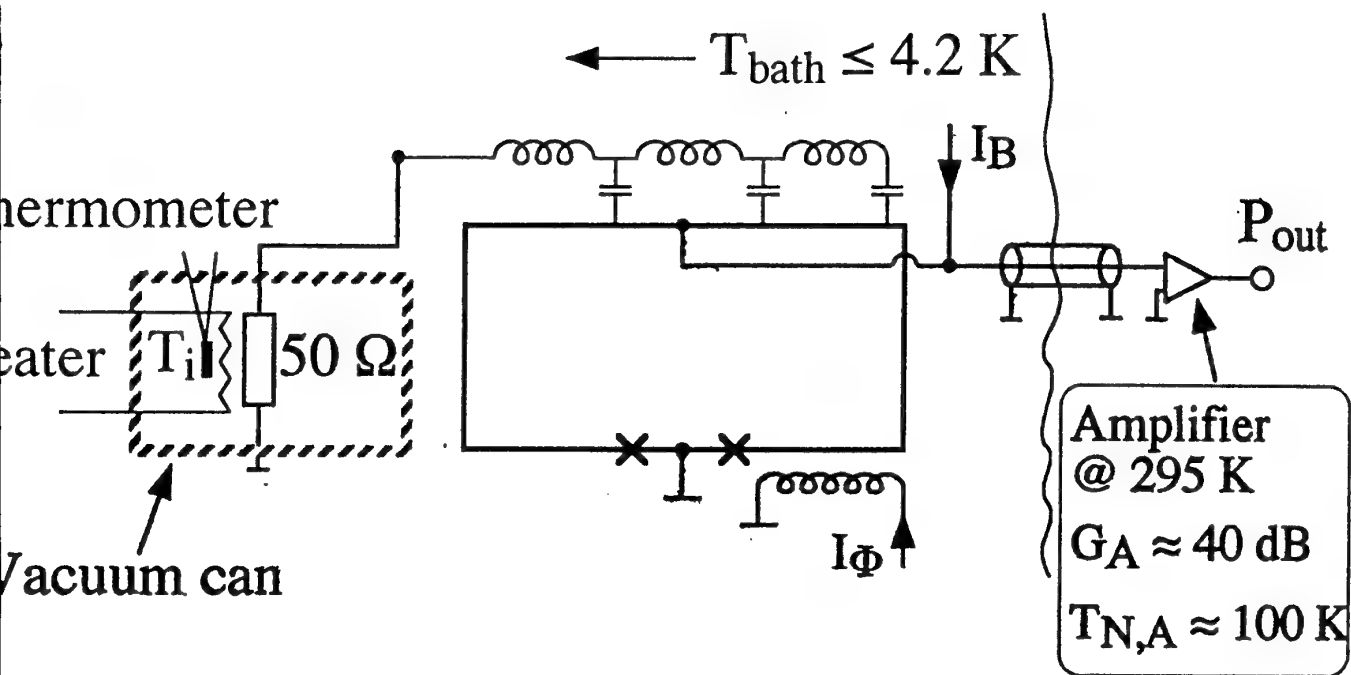
RESONANCE AT EXPECTED FREQUENCY

- HOLE & SLIT UNCOVERED :

RESONANT FREQUENCY DROPS BY FACTOR ~ 3

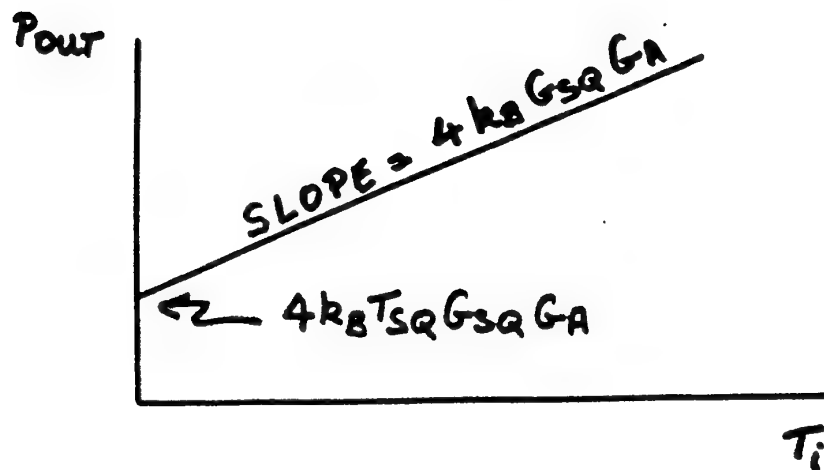
- HENCE IT APPEARS THAT INDUCTANCE COUPLED INTO THE COIL SLOWS THE WAVE VELOCITY.

Noise Temperature Measurements

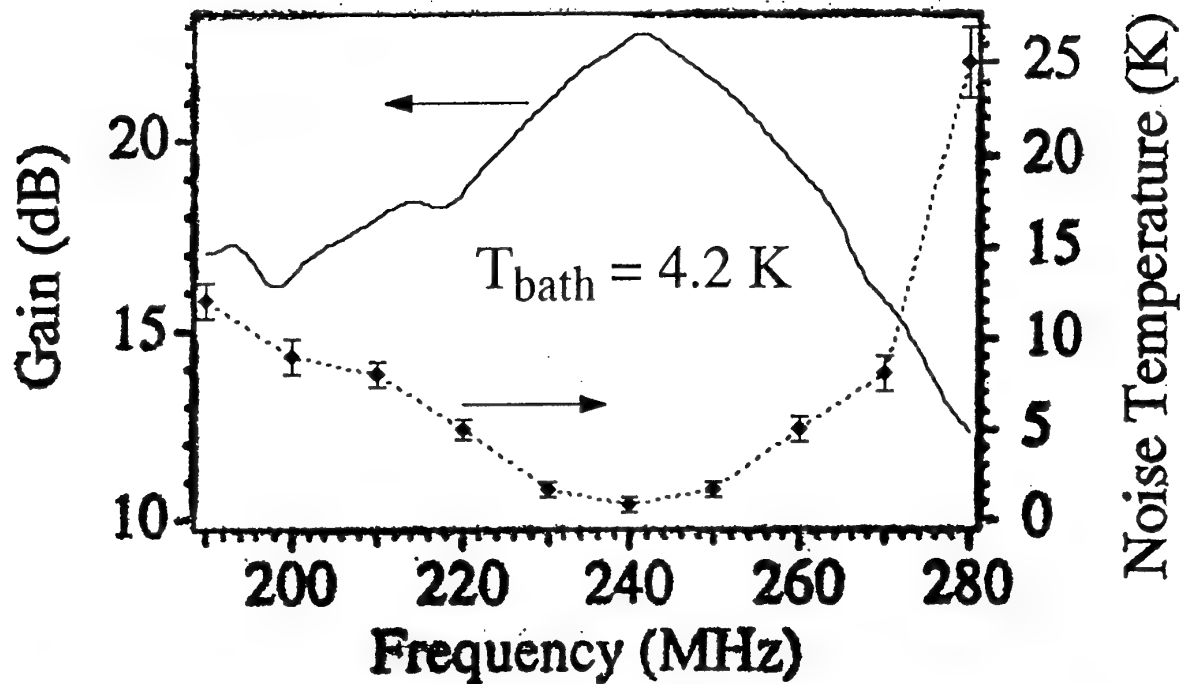


IF WE NEGLECT THE NOISE OF THE POSTAMPLIFIER

$$P_{\text{out}} = 4k_B (T_i + T_{SQ}) G_{SQ} G_A$$



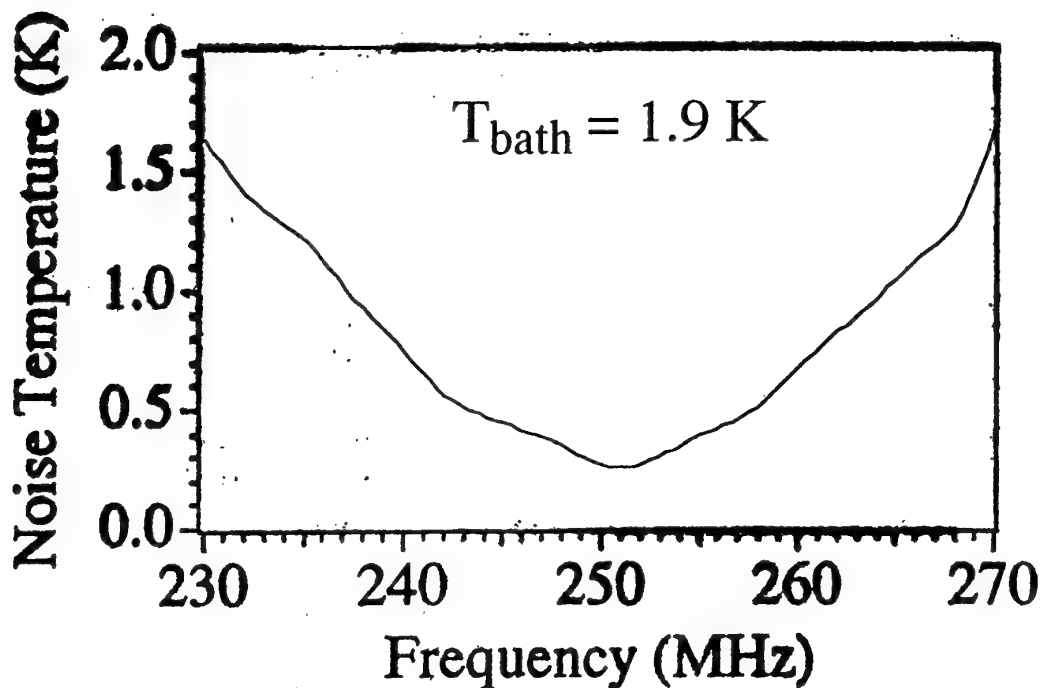
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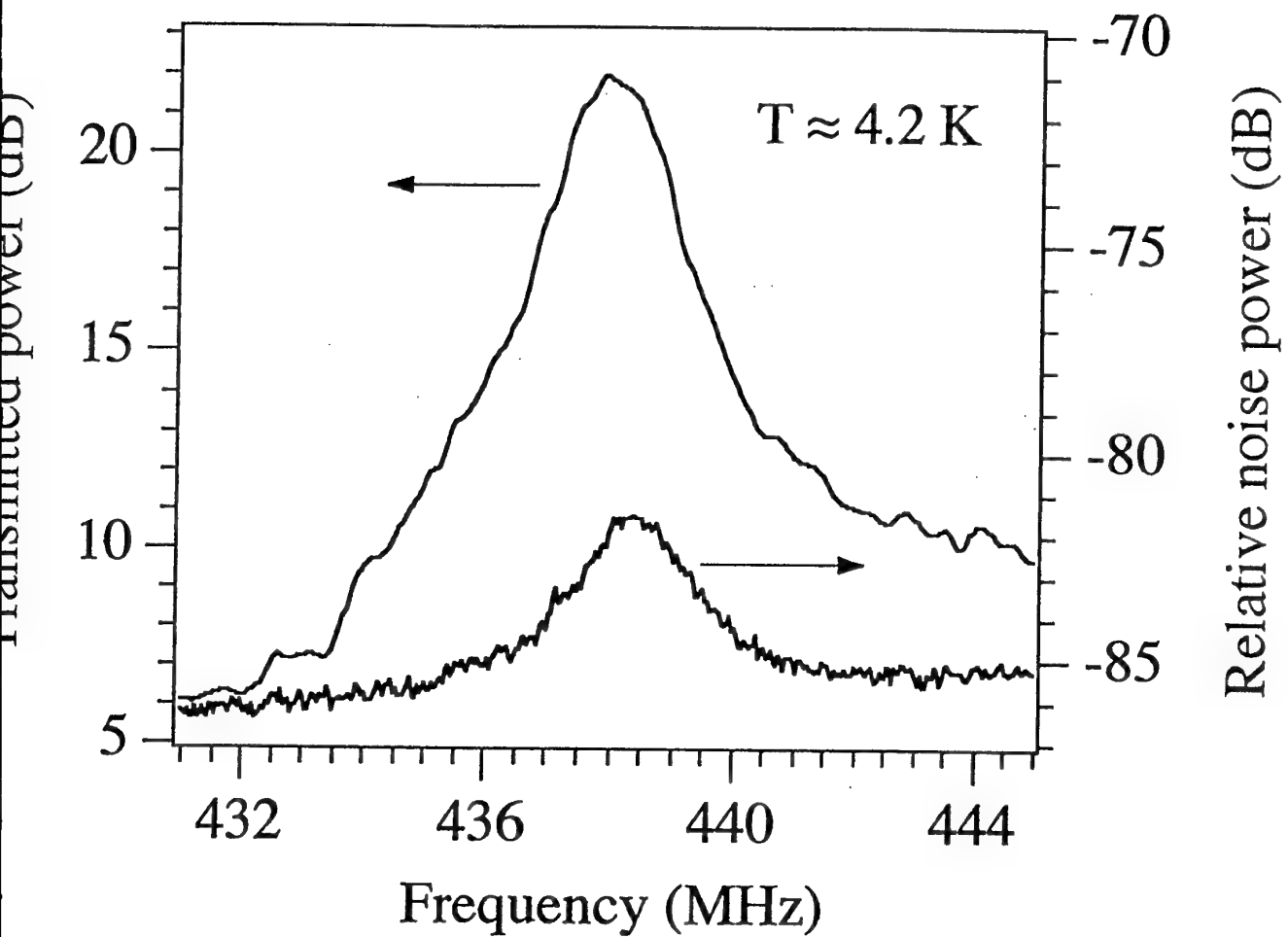


PERFORMANCE OF MICROSTRIP SQUID AMPLIFIERS
WITH COOLED HEMT POSTAMPLIFIER

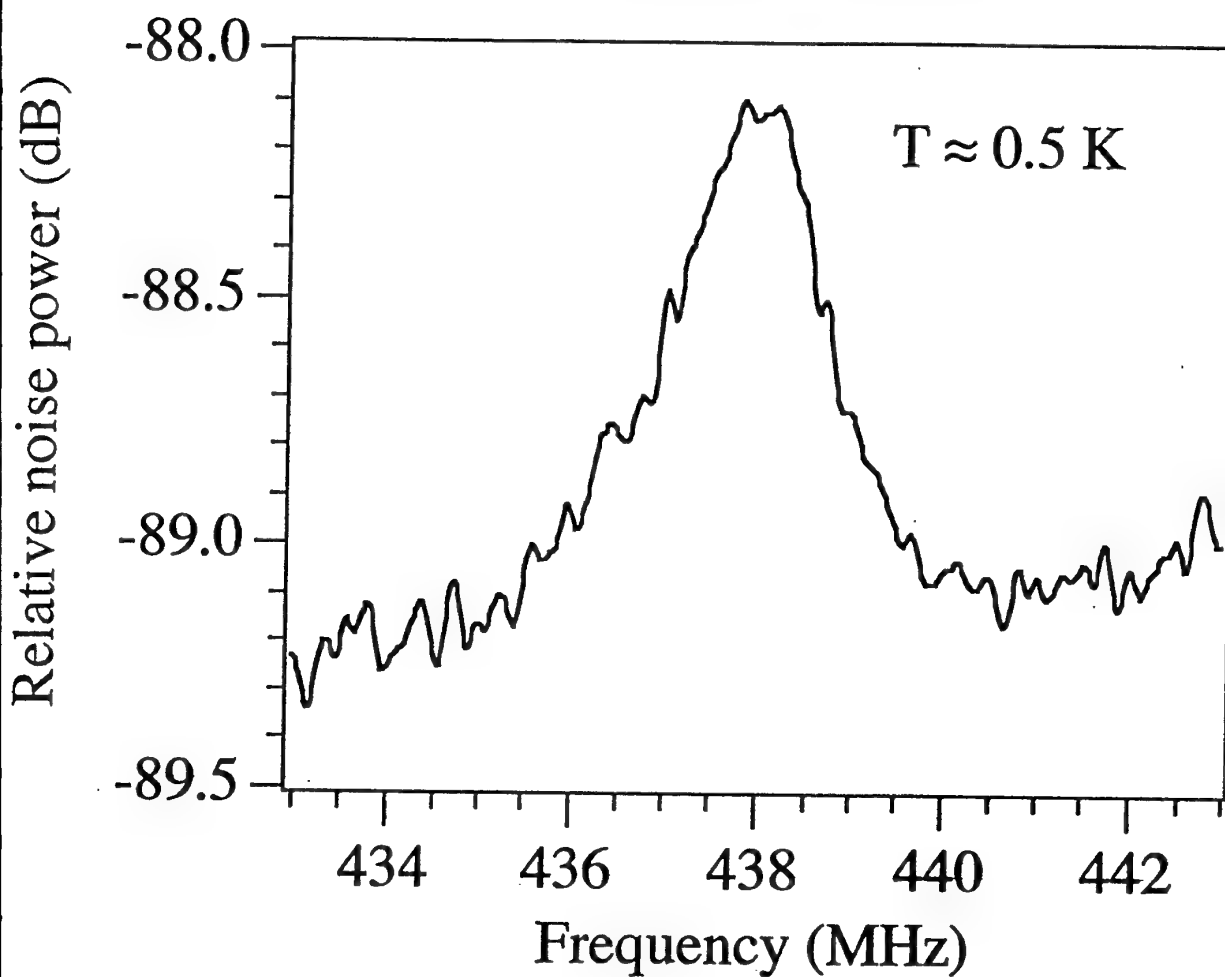
<u>FREQUENCY</u> (MHz)	<u>I</u>	<u>GAIN</u>	<u>T_N(SYS)</u>	<u>T_N(SQ)</u>
90	4.2	24	0.90 ± 0.12	0.86 ± 0.12
90	0.4	24.5	0.10 ± 0.02	0.06 ± 0.02
438	4.2	20	1.40 ± 0.18	1.02 ± 0.19
438	0.5	20	0.50 ± 0.07	0.12 ± 0.10

NOTE: AT 438 MHz, $T_N^{eq} = hf / k_B \ln 2 \approx \underline{0.03K}$

LC - Resonator Input



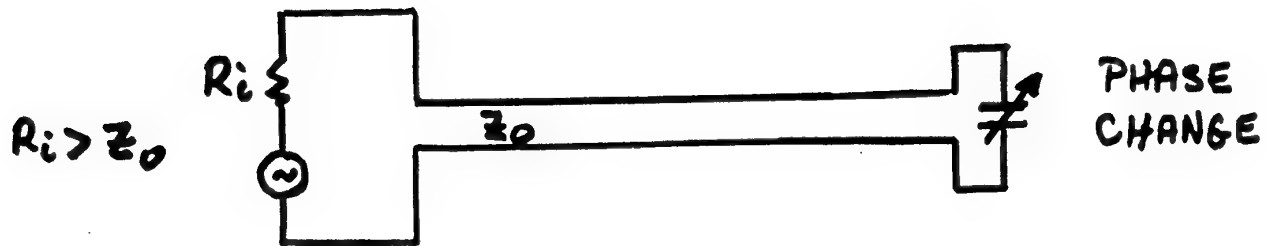
LC - Resonator Input



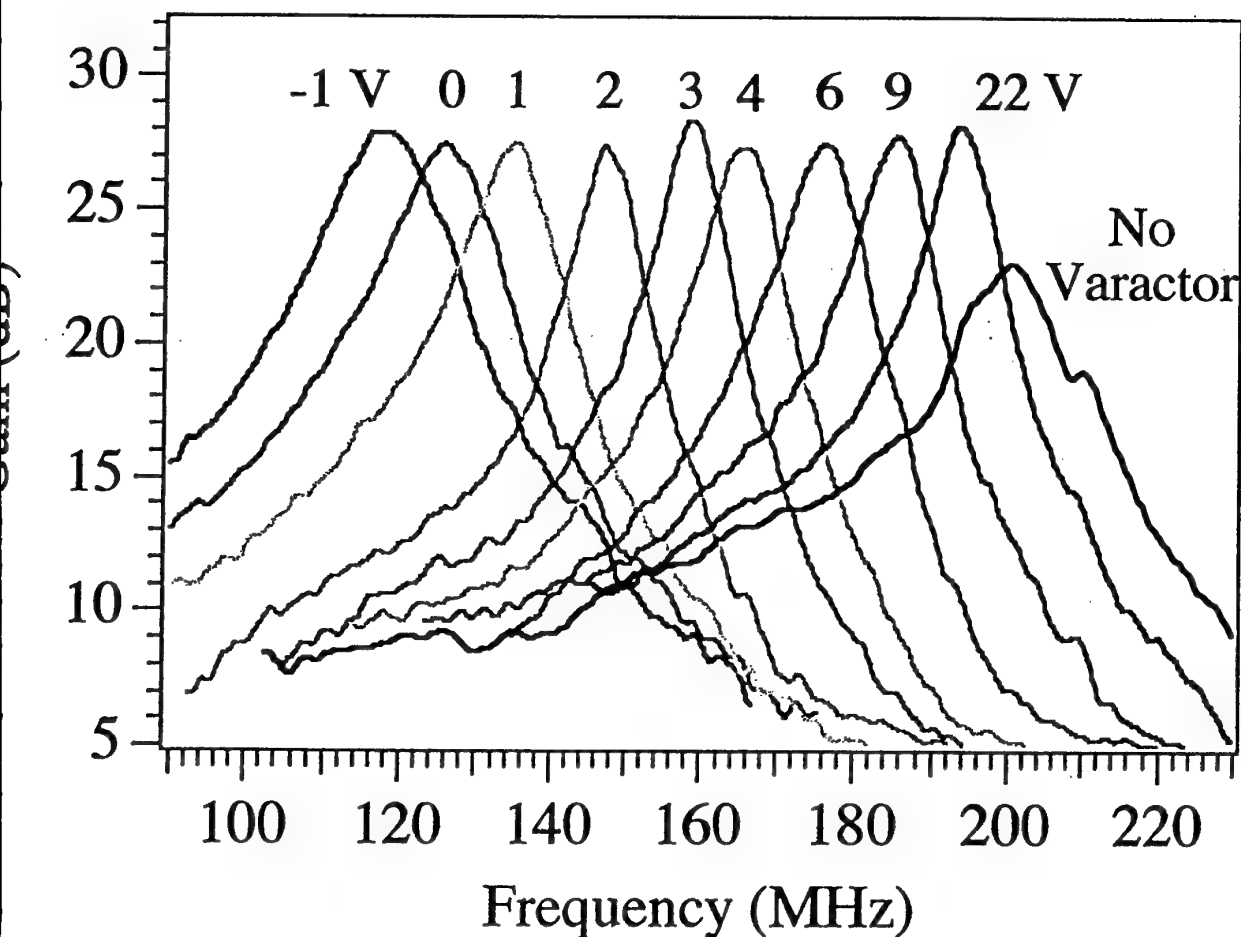
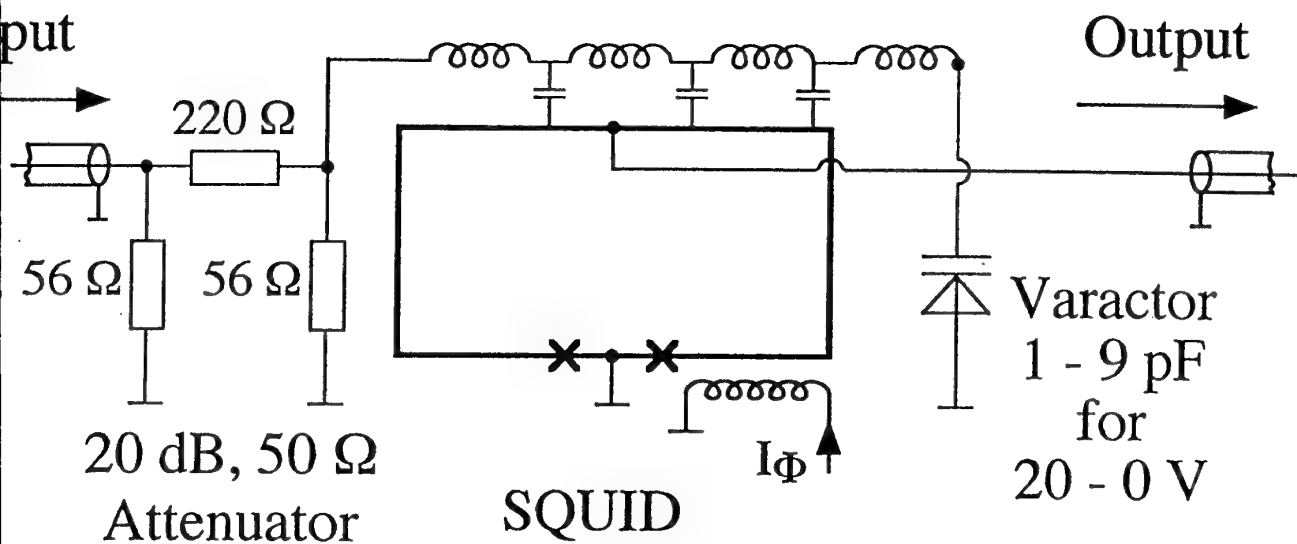
INFER $T_N^{(\text{SYS})} \approx \underline{0.5 \text{ K}}$

[MEASURED $T_N^{(\text{SYS})} = 0.50 \pm 0.07 \text{ K}$]

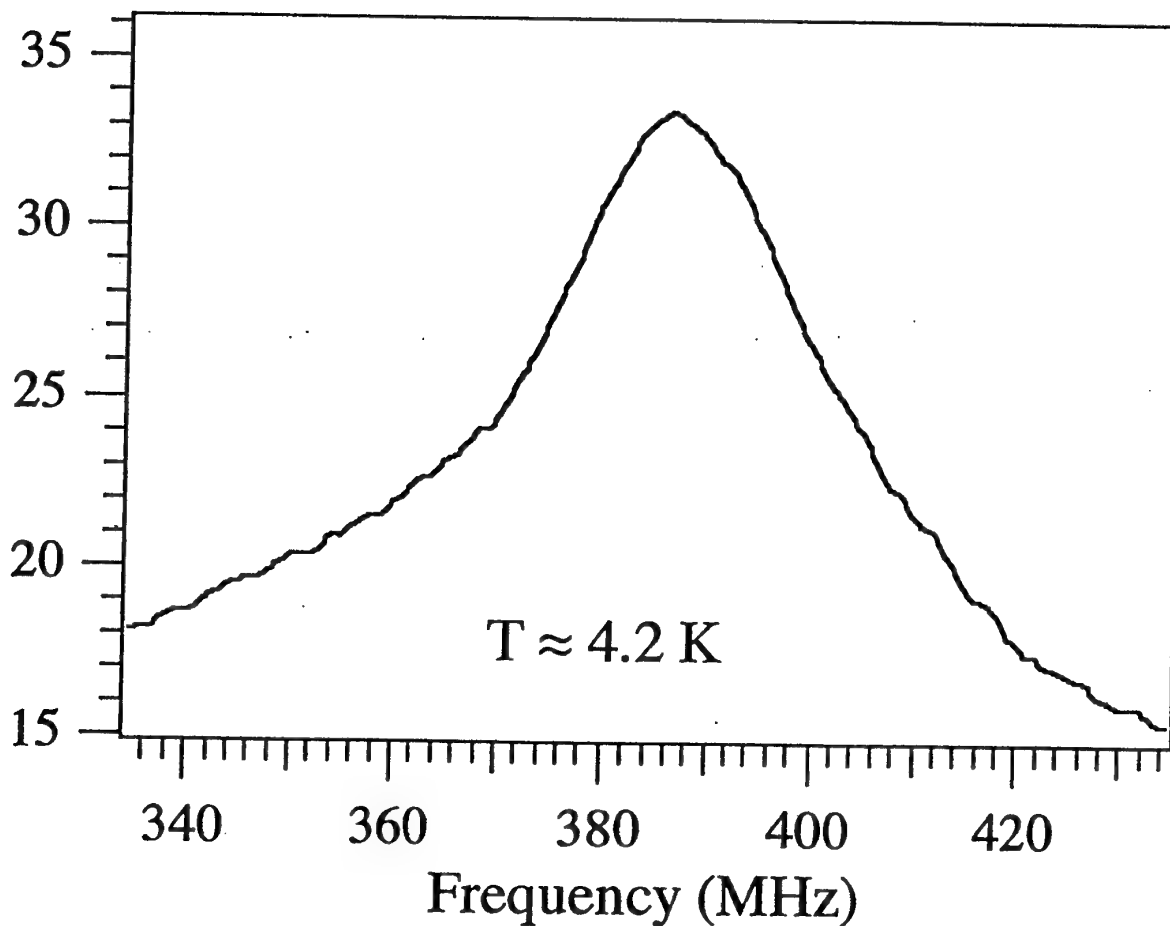
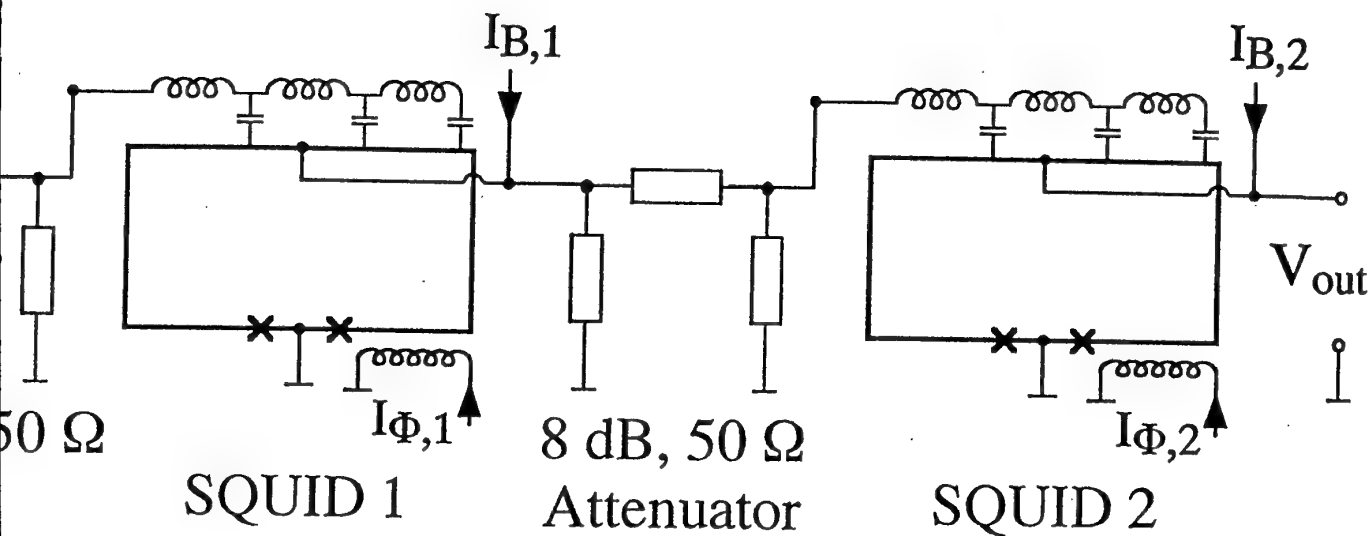
TERMINATION OF MICROSTRIP



Varactor tuning of microstrip SQUID



SQUID Postamplifier



Microstrip SQUID Amplifier: Summary

- Gain $\gtrsim 20$ dB for frequencies $\lesssim 1$ GHz
- With cooled postamplifier and $T = 0.4 - 0.5$ K:

$$T_N^{(SQ)} \sim 0.1 \text{ K}$$

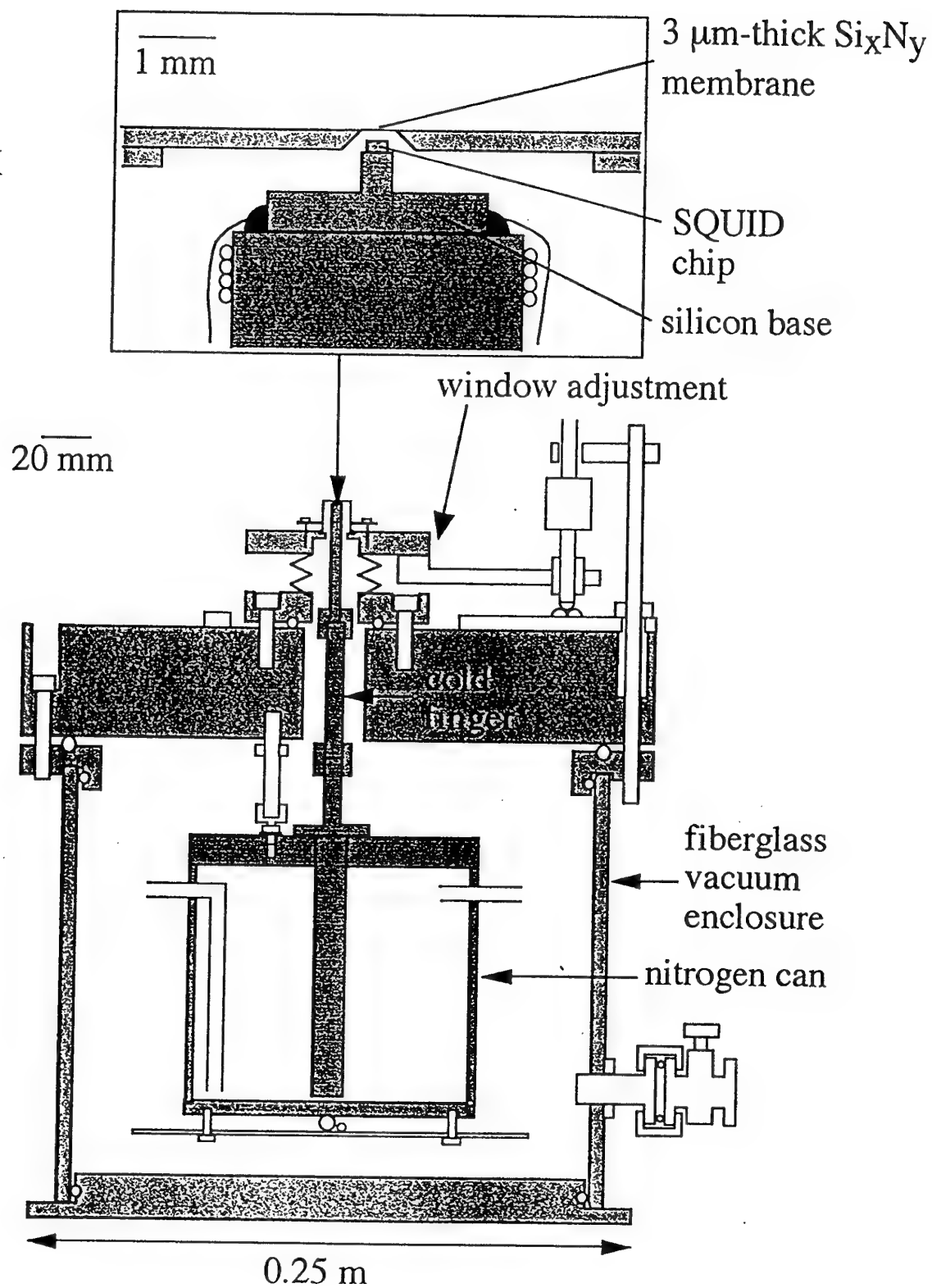
- Tunable over factor of 2 with varactor diode
- Second SQUID used as postamplifier
- Cooled to 0.1 K, SQUID should be

Quantum Limited ($f \gtrsim 1/2$ GHz)

Magnetotactic Bacteria

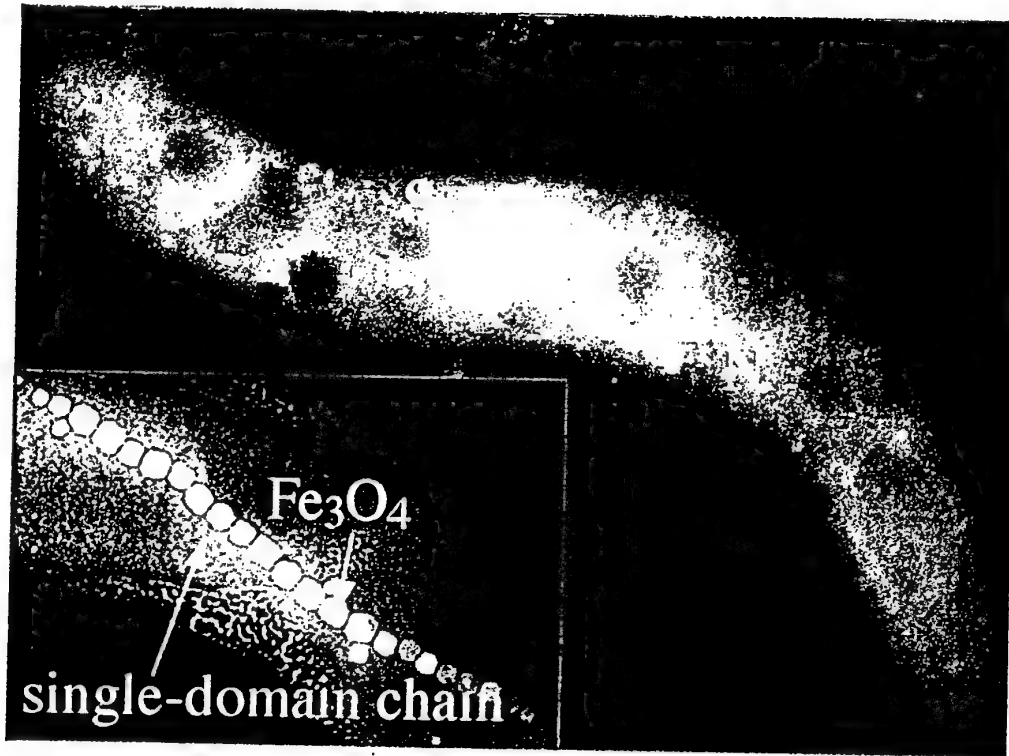
- Yann Chemla
Helene Grossman
Tom Lee
- Bob Buchanan -- Microbiology
Mike Adamkiewicz

MICROSCOPE SCHEMATIC



Magnetotactic Bacteria

Bacteria MS-1 (*Magnetospirillum magnetotacticum*):

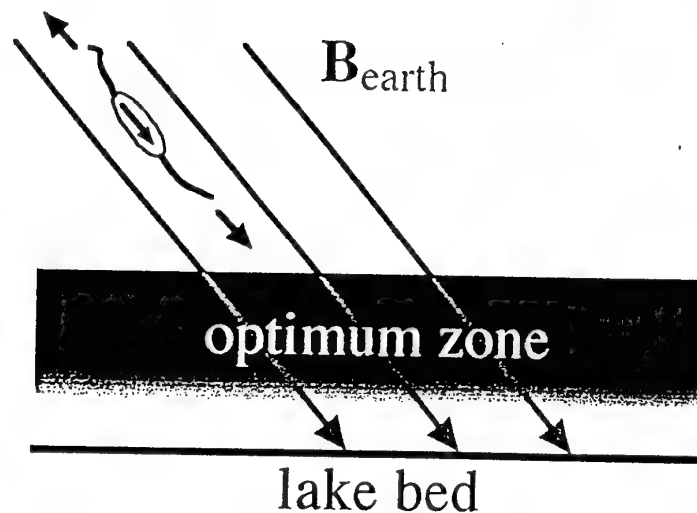


$$m \sim 10^{-16} \text{ Am}^2$$

Magnetotaxis:

- $m \cdot B \sim 10 \text{ k}_B T$

- 3-D \Rightarrow 1-D

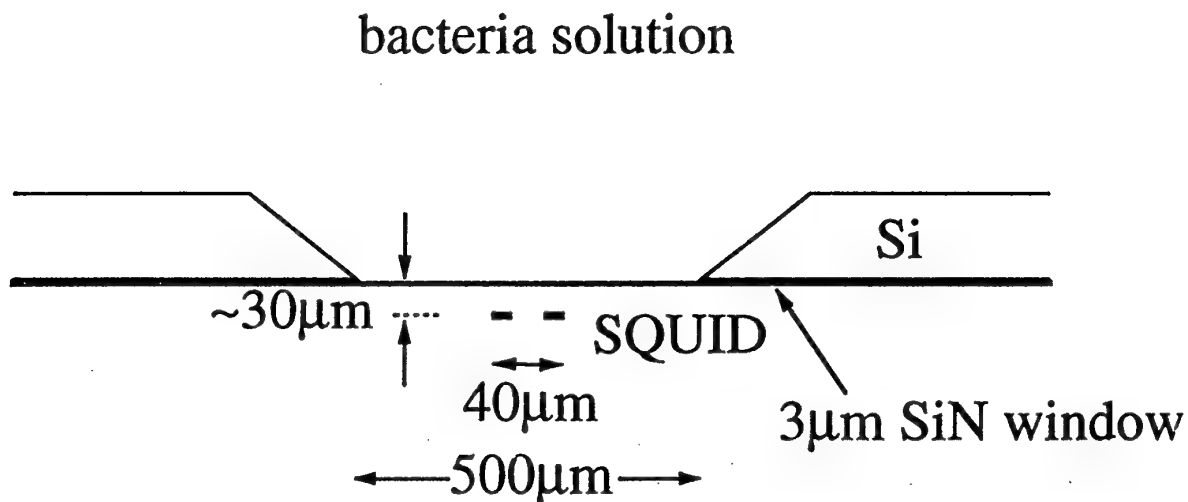


A. S. Bahaj, et. al. <http://www.soton.ac.uk>)

R. P. Blakemore (1982) *Ann. Rev. Microbiol.* **36**, 217-38)

Experimental Setup

- Observe bacteria in solution
- Parameters:
 - shielded environment ($B < 2 \times 10^{-5} B_e$)
 - cell concentrations: 10^7 - 10^8 cells/ml
 - SQUID $\sim 30\mu\text{m}$ away



- Measurement:

motion of bacteria in solution



magnetic flux fluctuations

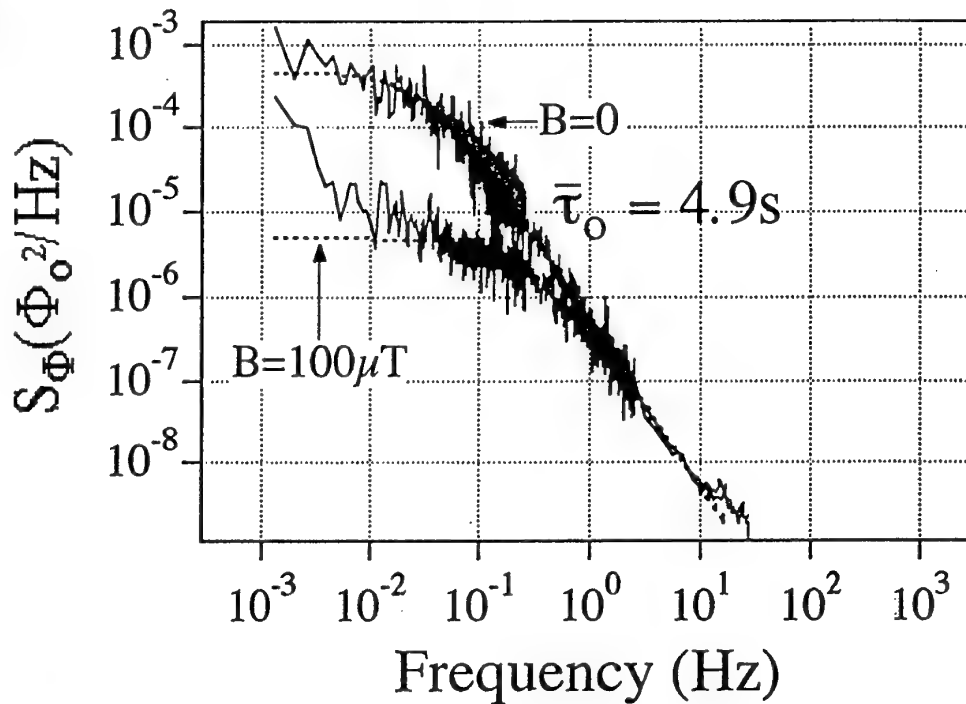


measure flux noise spectral density: $S_\Phi(f)$

Dead Bacteria

Rotational Brownian motion of magnetic dipoles:

$$\Rightarrow S_{\Phi}(f) \sim \frac{2\tau_o}{1 + (2\pi\tau_o f)^2} \quad \begin{array}{l} \tau_o = \alpha_r/2k_B T, \\ \alpha_r = \text{rotational drag coeff.} \end{array}$$



Model bacteria as cylinders:

$$\tau_o \approx \frac{\pi\eta L^3}{6k_B T} \left(\ln \frac{L}{d} - 0.662 + 0.92 \frac{d}{L} \right)^{-1}$$

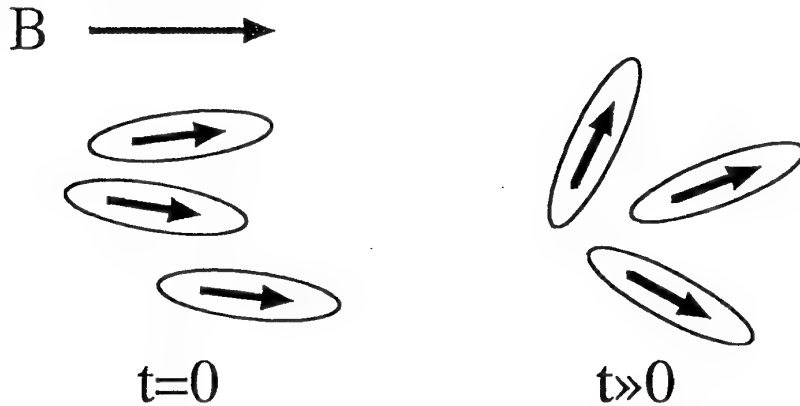
For $d \sim 0.7 \mu\text{m} \Rightarrow L \approx 3.5 \mu\text{m}, \Delta L \approx 0.7 \mu\text{m}$

In a field, noise is reduced and $\tau_o \Rightarrow \tau_B = \alpha_r/2mB$
 $\Rightarrow m = 3.0 \times 10^{-16} \text{ Am}^2$

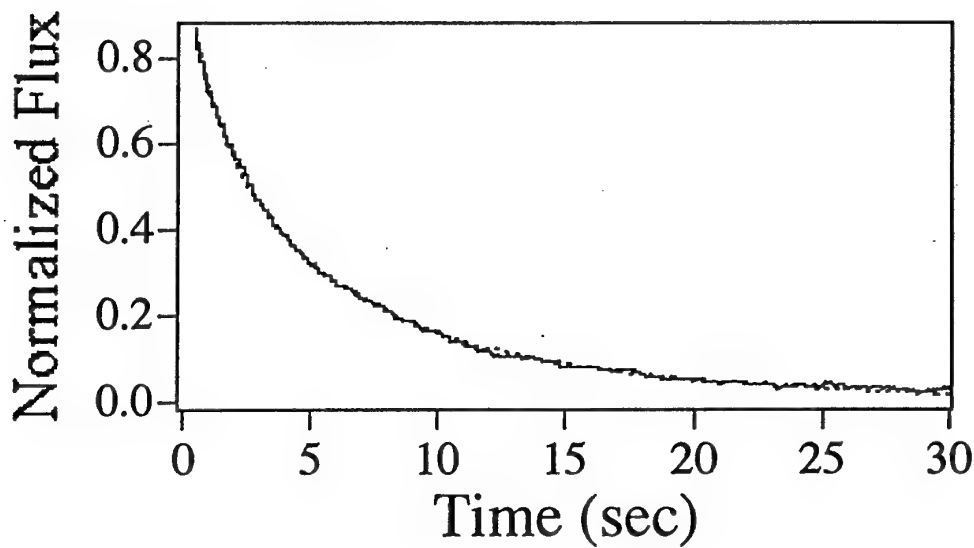
(M. M. Tirado, et al (1980) *J. Chem. Phys.* **73**(4), 1986-93)

Relaxation in a Field

- Turn off a field & measure randomization time:



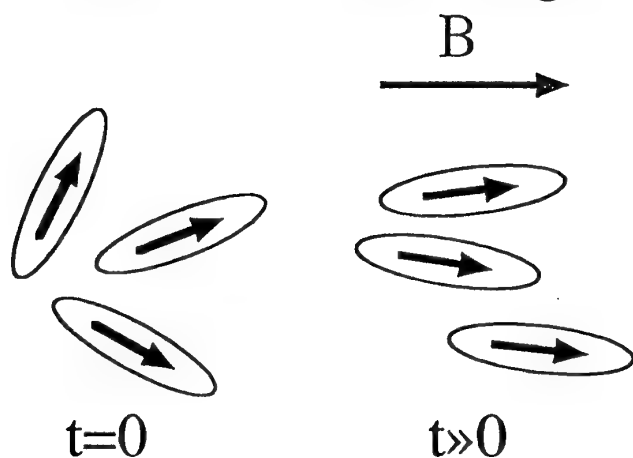
$$\Rightarrow \Phi(t) \sim e^{-t/\tau_o}$$
$$\tau_o = \alpha_r / 2k_B T$$



$$\Rightarrow \bar{\tau}_o = 4.8s$$

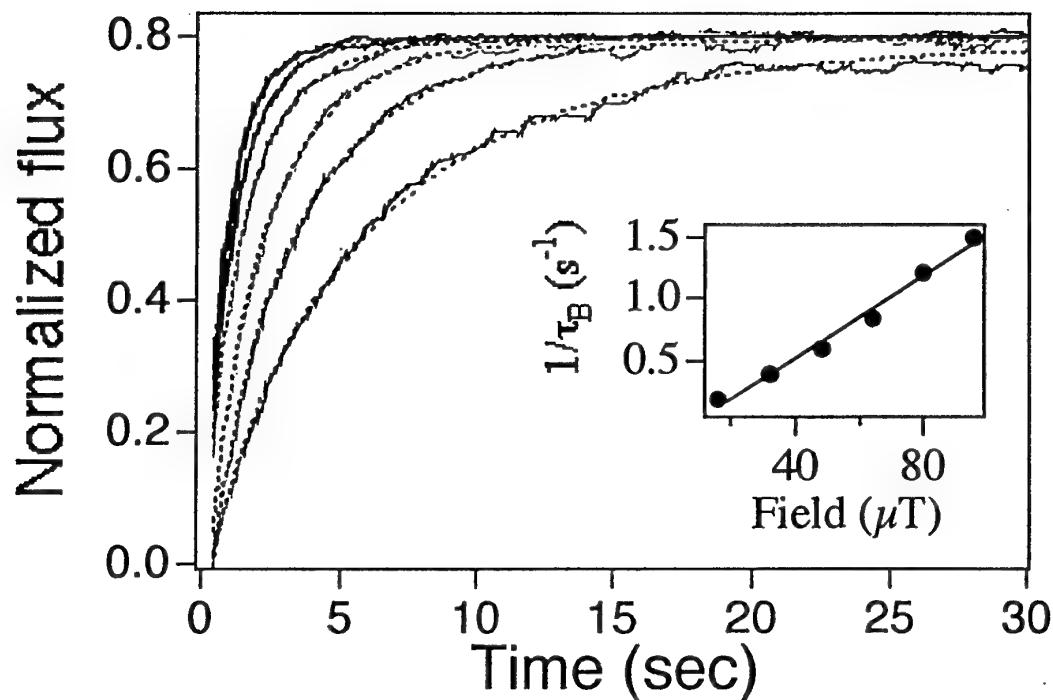
Alignment in a Field

- Turn on a field & measure alignment time:



$$\Rightarrow \Phi(t) \sim e^{-t/\tau_B}$$

$$\tau_B = \alpha_r / 2mB$$

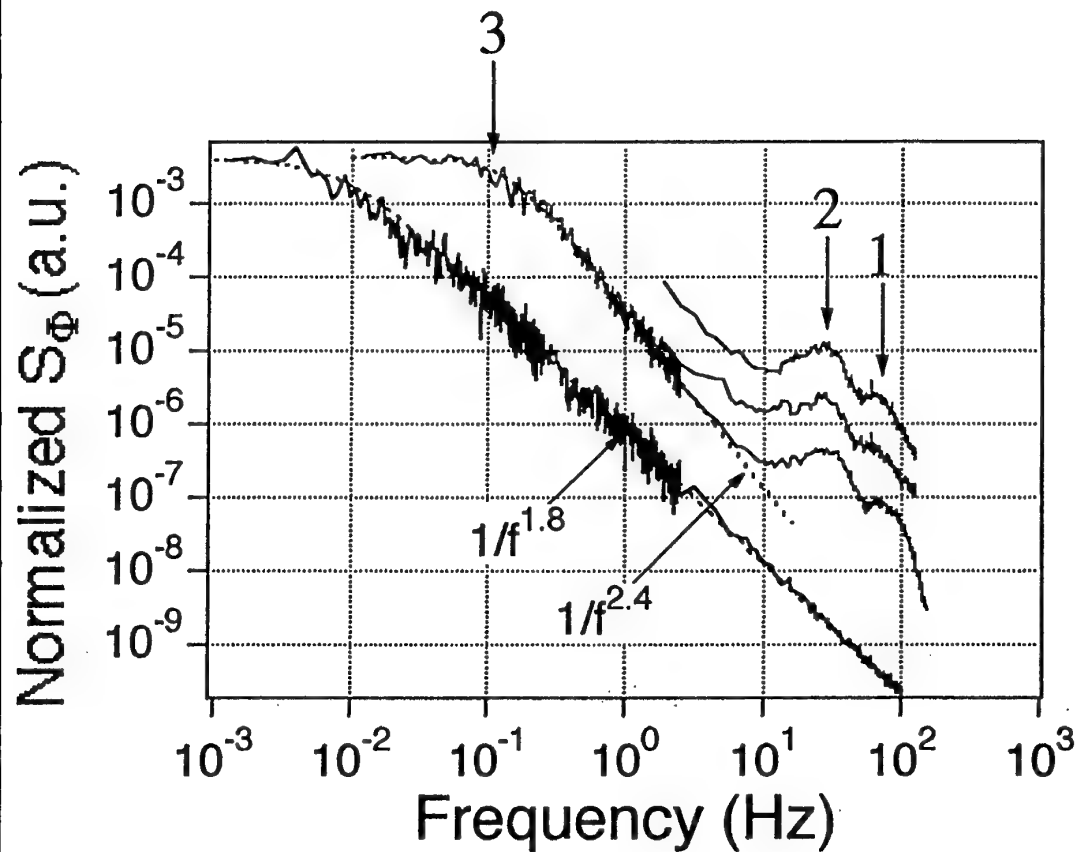


$$\Rightarrow m = 3.2 \times 10^{-16} \text{ Am}^2$$

Live Bacteria

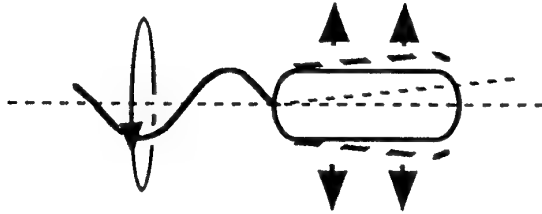
universal features:

- high frequency peaks: (1) $\sim 65\text{Hz}$, (2) $\sim 25\text{Hz}$
- shift in low freq. knee: (3) $\sim 0.1\text{Hz}$
- deviation from Lorentzian

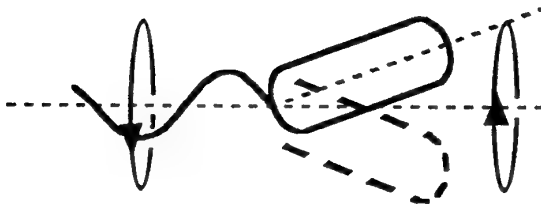


Modeling

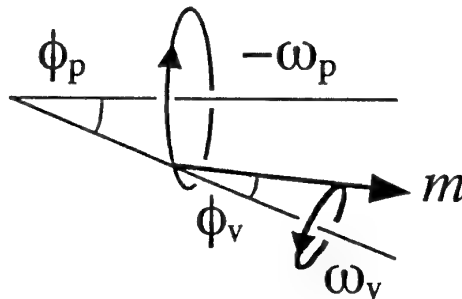
- Vibration or “gyration”
 - imbalance in drag forces
 - vibration at flagellar frequency $\sim 100\text{Hz}$



- Precession or “wobble”
 - body rolls counter to flagellum
 - body & flagellar axes not collinear
 - precession at lower frequency



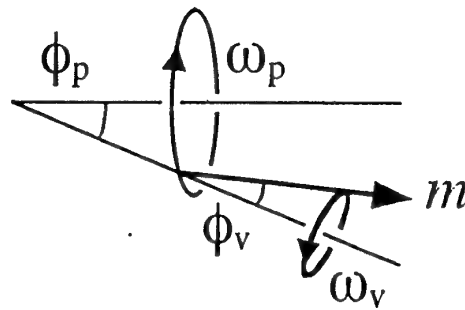
- Model vibration & precession as rotations of dipole about two axes:



- In lab frame, measure peaks at f_p and $f_v - f_p$.

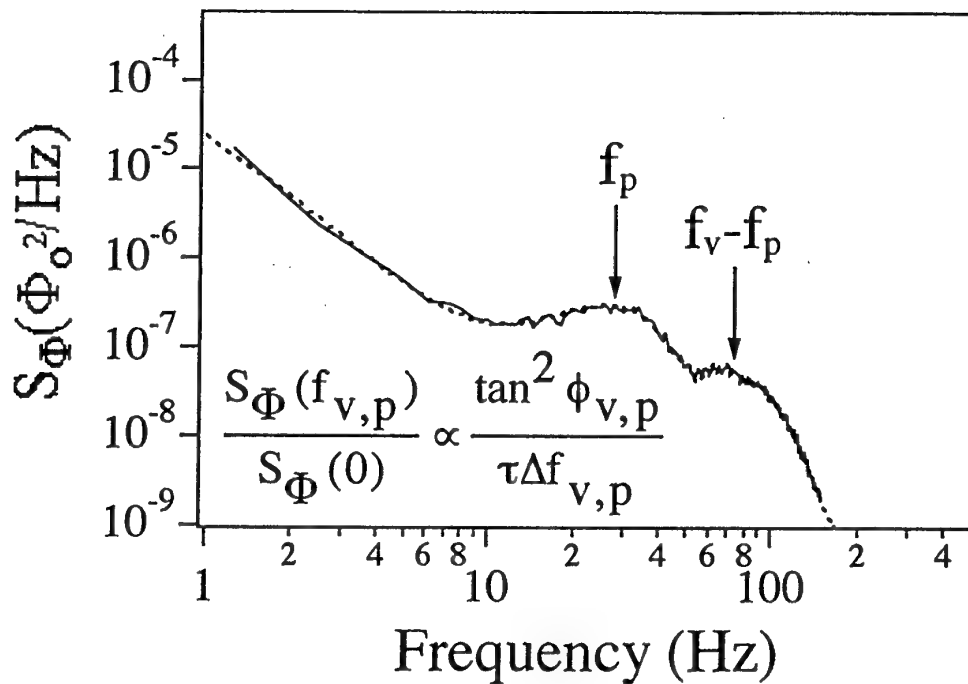
High Frequency Behavior

Model vibration & precession as rotations of dipole about two axes:



Fit spectrum to Gaussian distribution of frequencies:

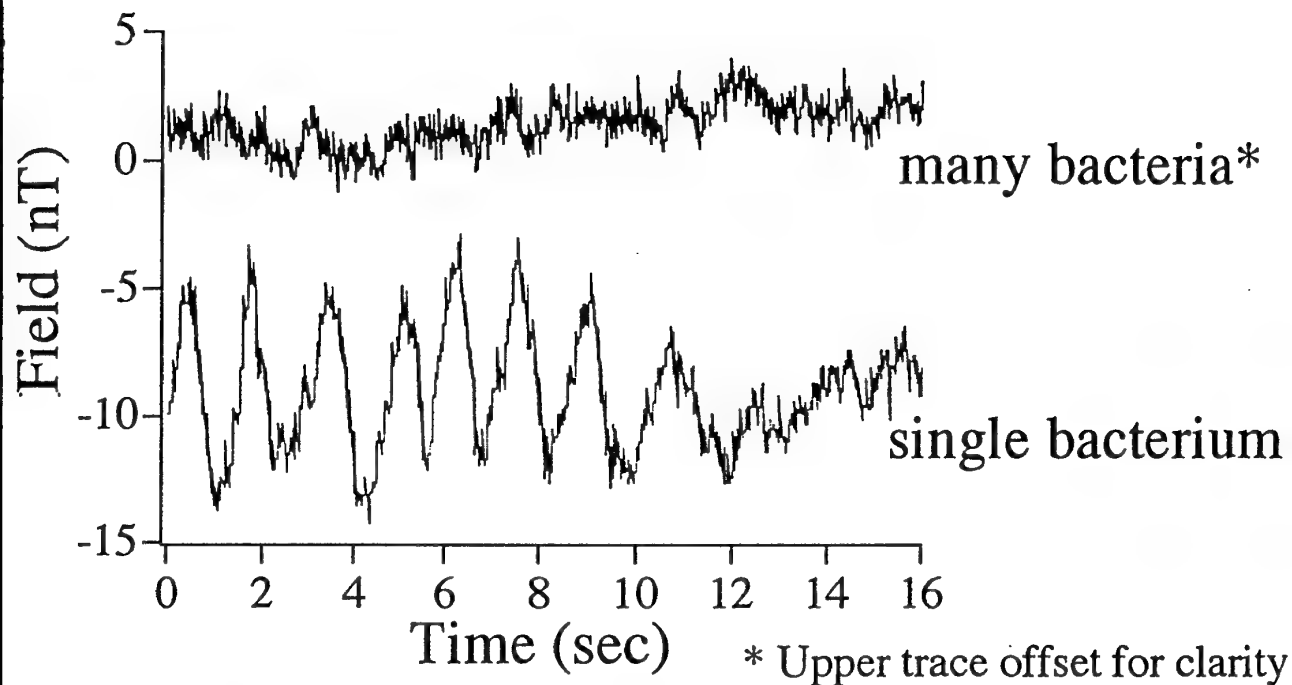
- ϕ_v , ϕ_p determined by scaling to $S_\Phi(f=0)$



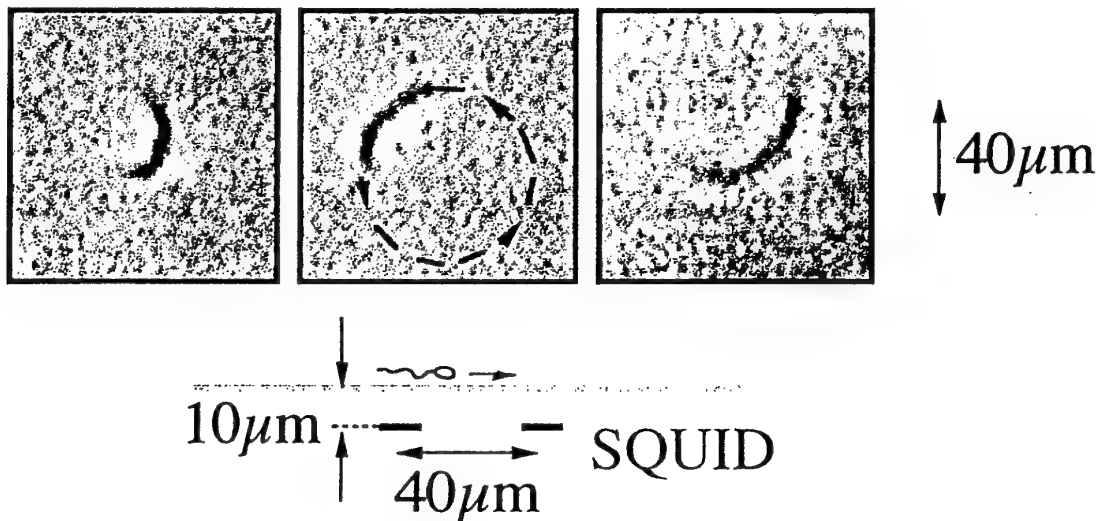
$$f_v = 89 \text{ Hz}, \Delta f_v = 30 \text{ Hz}, \phi_v = 5.5^\circ$$

$$f_p = 26 \text{ Hz}, \Delta f_p = 10 \text{ Hz}, \phi_p = 7.0^\circ$$

Time scan of single bacterium



Interpretation: orbits near surfaces



Amplitude and period consistent

Sensitivity: $<10^{-17} \text{ Am}^2$ in 1Hz \Leftrightarrow one 35nm particle $\sim 15\text{-}30\mu\text{m}$ away

P. D. Frymier, et al (1995) *Proc. Natl. Acad. Sci USA* **92**, 6195-99)

MAGNETIC MOMENT RESOLUTION

- MAGNETIC MOMENT OF ONE BACTERIUM $\approx 3 \times 10^{-16} \text{ Am}^2$
- S/N RATIO OF SWIMMING BACTERIUM
 $\approx 20:1$ IN 25 Hz BANDWIDTH
- THUS, MICROSCOPE RESOLUTION $\approx 3 \times 10^{-18} \text{ Am}^2 / \text{Hz}^{1/2}$
 $\approx 3 \times 10^5 \mu_B / \text{Hz}^{1/2}$
- NOTE: EACH BACTERIUM CONTAINS ~ 30 MAGNETOSOMES
WITH A MAGNETIC MOMENT $\sim 10^{-17} \text{ Am}^2$
THUS, ONE COULD DETECT 1 MAGNETOSOME
WITH A S/N RATIO $\sim 3 (\text{Hz}^{-1/2})$

Immunoassay

{ Physikalisch Technische Bundesanstalt, Berlin
Institut für Diagnostikforschung GmbH, Berlin
Schering Ag, Berlin

Magnetically tag antibody

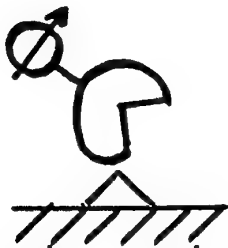


Attach antigen to substrate

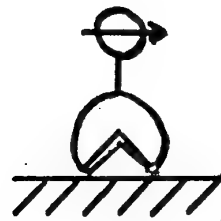


Allow interaction to take place

Apply magnetic field for a few seconds



Brownian rotation of antibody yields zero average magnetic field



Remanent magnetization of magnetic tag produces nonzero field

MAGNETIC FIELD GRADIENTS

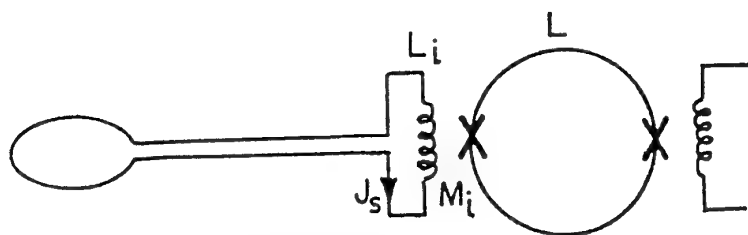
MAGNETIC DIPOLE MOMENT m

$$B \sim \frac{m}{r^3}$$

$$\frac{dB}{dr} \sim \frac{m}{r^4}$$

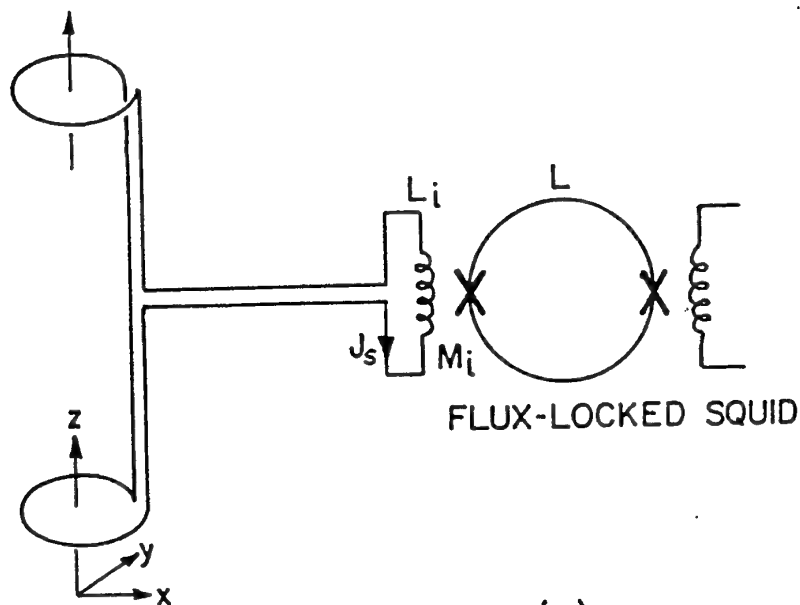
$$\frac{d^2B}{dr^2} \sim \frac{m}{r^5}$$

FLUX TRANSFORMERS

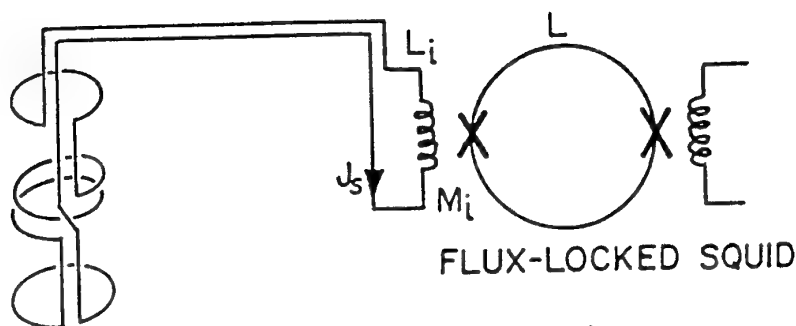


$B_N \sim 10^{-15} \text{ T Hz}^{-1/2} = 10^{-11} \text{ gauss Hz}^{-1/2}$ FLUX-LOCKED SQUID

(a)



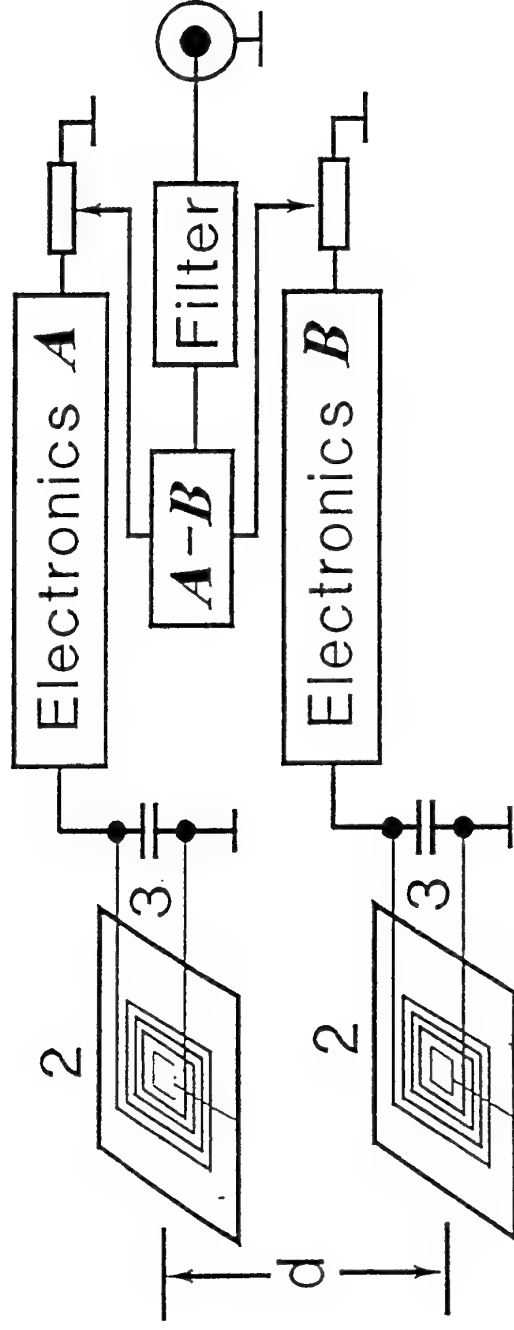
(b)



(c)

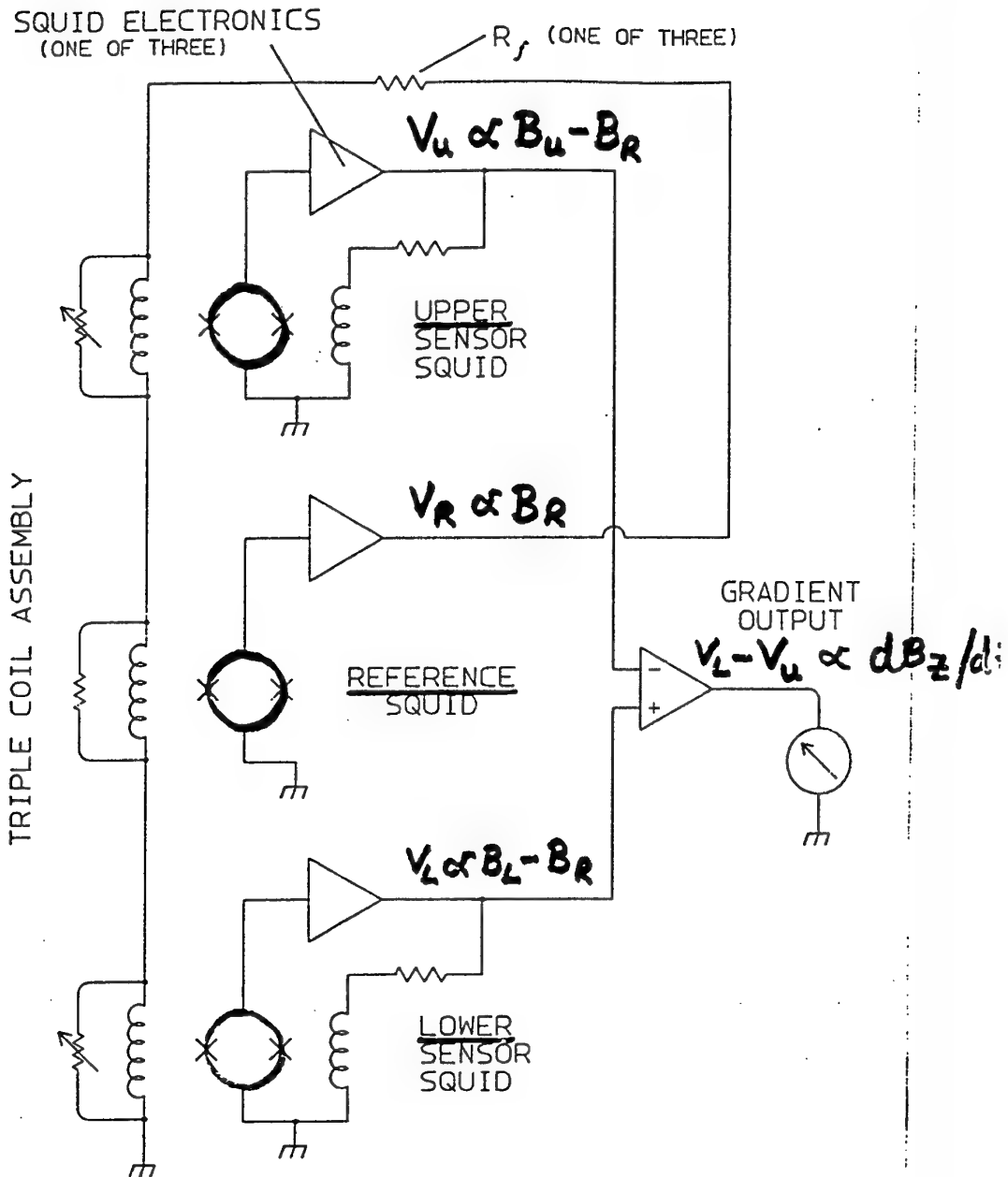
XBL 766-7138A

JÜLICH GRADIOMETER (TAVRIN ET AL.)



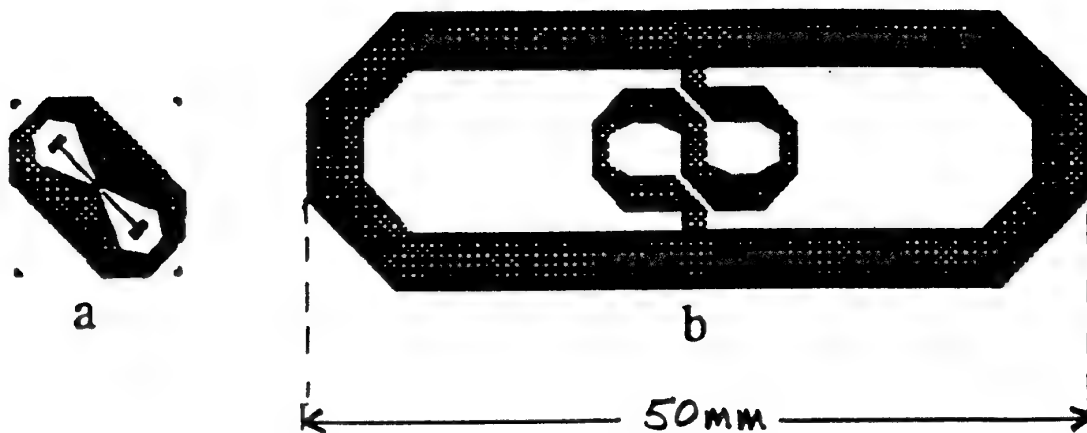
ALSO : 2ND DERIVATIVE

THREE - SQUID GRADIOMETER (KOCH ET AL.)



- REFERENCE SQUID PROVIDES QUIET ENVIRONMENT FOR UPPER AND LOWER SQUIDS
- NOISE OF REFERENCE SQUID IS SUBTRACTED OUT

PLANAR GRADIOMETER



FALEY ET AL. (JÜLICH)

BALANCE: 1 PART IN 1800

$5 \text{ pT m}^{-1} \text{ Hz}^{-1/2}$ AT 1 kHz

Collaborators

UCB/LBNL

Sherry Cho
Gene Dantsker
Oliver Froelich
Achim Kittel
Konstantin Kouznetsov
Robert McDermott
Byungdu Oh
Saburo Tanaka
JÖRG BORGMANN

Conductus, Inc.

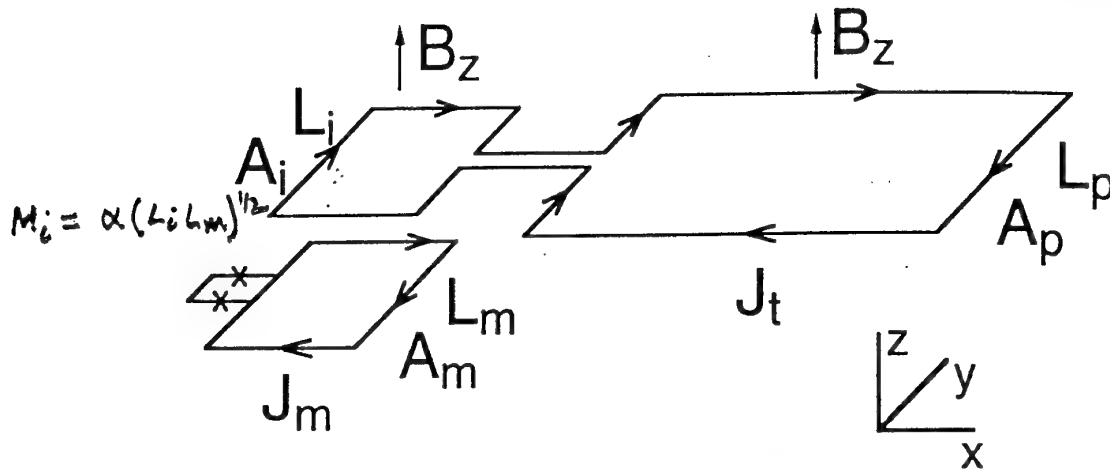
Kookrin Char
Z. Lu
Vlad Matijasevic
C. Soble

IBM

Roger Koch

FLIP-CHIP GRADIOMETER: PRINCIPLE

ZIMMERMAN 1977



$$M_i = \alpha (L_i L_m)^{1/2}$$

CONDITION FOR BALANCE : ZERO RESPONSE TO UNIFORM B_z

TRANSFORMER: $B_z (A_p + A_i) - (L_p + L_i) J_t - M_i J_m = 0$

MAGNETOMETER: $B_z A_m - L_m J_m - M_i J_t = 0$

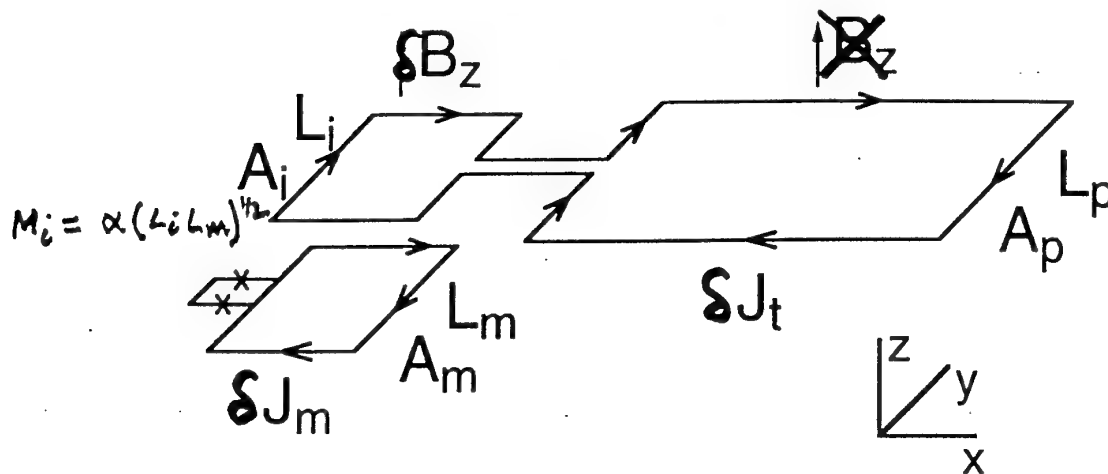
REGARD α AS THE VARIABLE PARAMETER, CHOOSING IT SO THAT $J_m = 0$:

$$\alpha = \frac{A_m}{A_p + A_i} \cdot \frac{L_p + L_i}{(L_i L_m)^{1/2}}$$

THIS IS THE CONDITION TO BALANCE THE GRADIOMETER

FLIP-CHIP GRADIMETER: PRINCIPLE

ZIMMERMAN 1977



GRADIENT RESPONSE: APPLY δB_z TO MAGNETOMETER
AND INPUT LOOP ONLY

TRANSFORMER: $\delta B_z A_i - (L_p + L_i) \delta J_t - M_i \delta J_m = 0$

MAGNETOMETER: $\delta B_z A_m - L_m \delta J_m - M_i \delta J_t = 0$

SOLVING FOR δJ_m :

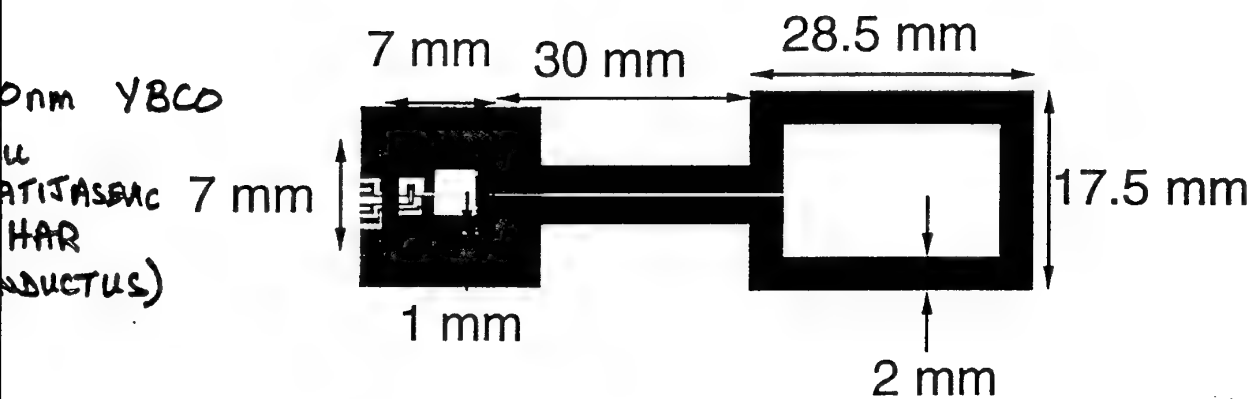
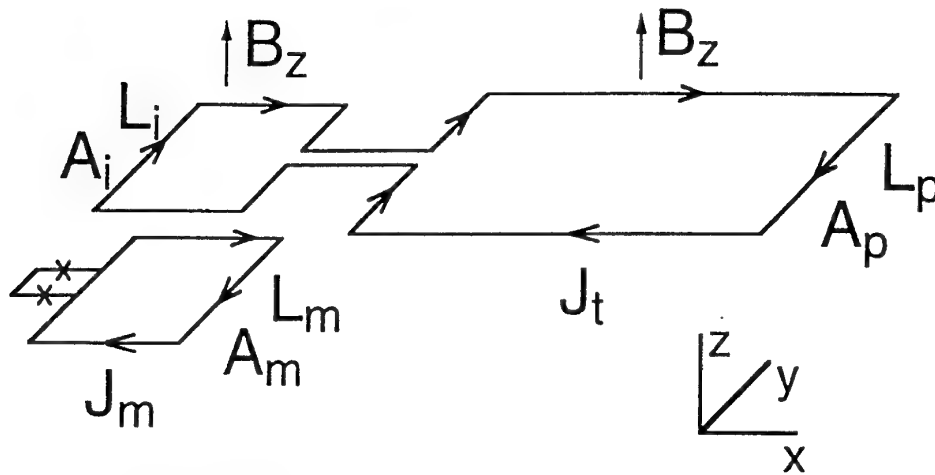
$$\delta J_m = \eta \left[\delta B_z \frac{A_m}{L_m} \right]$$

CURRENT IN BARE MAGNETOMETER

WHERE $\eta = \frac{L_p/L_i + 1 - \alpha(A_i/A_m)(L_m/L_i)^{1/2}}{L_p/L_i + 1 - \alpha^2}$

FACTOR η REPRESENTS THE REDUCTION IN THE SENSITIVITY OF THE MAGNETOMETER DUE TO THE TRANSFORMER

FABRICATION OF GRADIOMETER



ESTIMATED PARAMETERS:

TRANSFORMER: $L_i \approx 10 \text{ nH}$, $A_i \approx 36 \text{ mm}^2$, $L_p \approx 50 \text{ nH}$, $A_p \approx 411 \text{ mm}^2$

SQUID: $L \approx 50 \text{ pH}$, $R \approx 1.2 \Omega$, $I_0 \approx 200 \mu\text{A}$

MAGNETOMETER: $L_m \approx 4 \text{ nH}$, $A_m \approx 20 \text{ mm}^2$

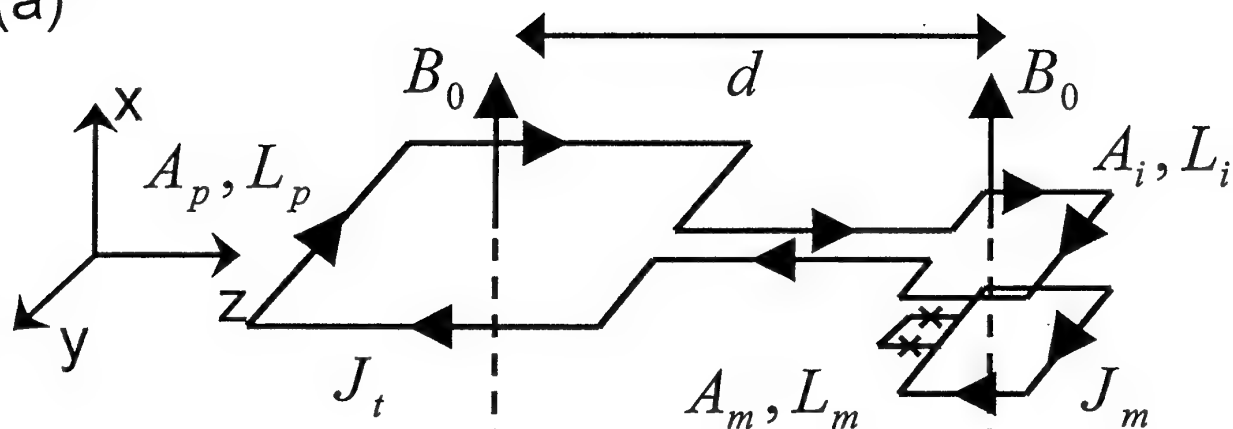
THUS: $\alpha = 0.43$

$\eta = 0.95$ - ONLY 5% REDUCTION IN SENSITIVITY

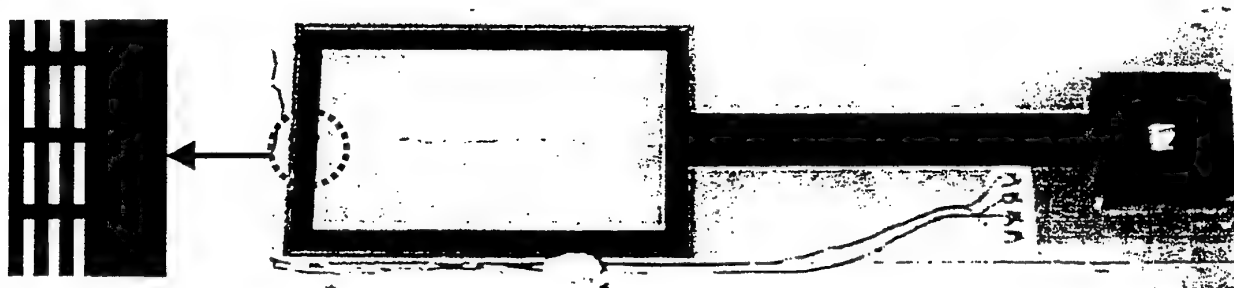
BASELINE: 48 mm

First-order asymmetric gradiometer

(a)

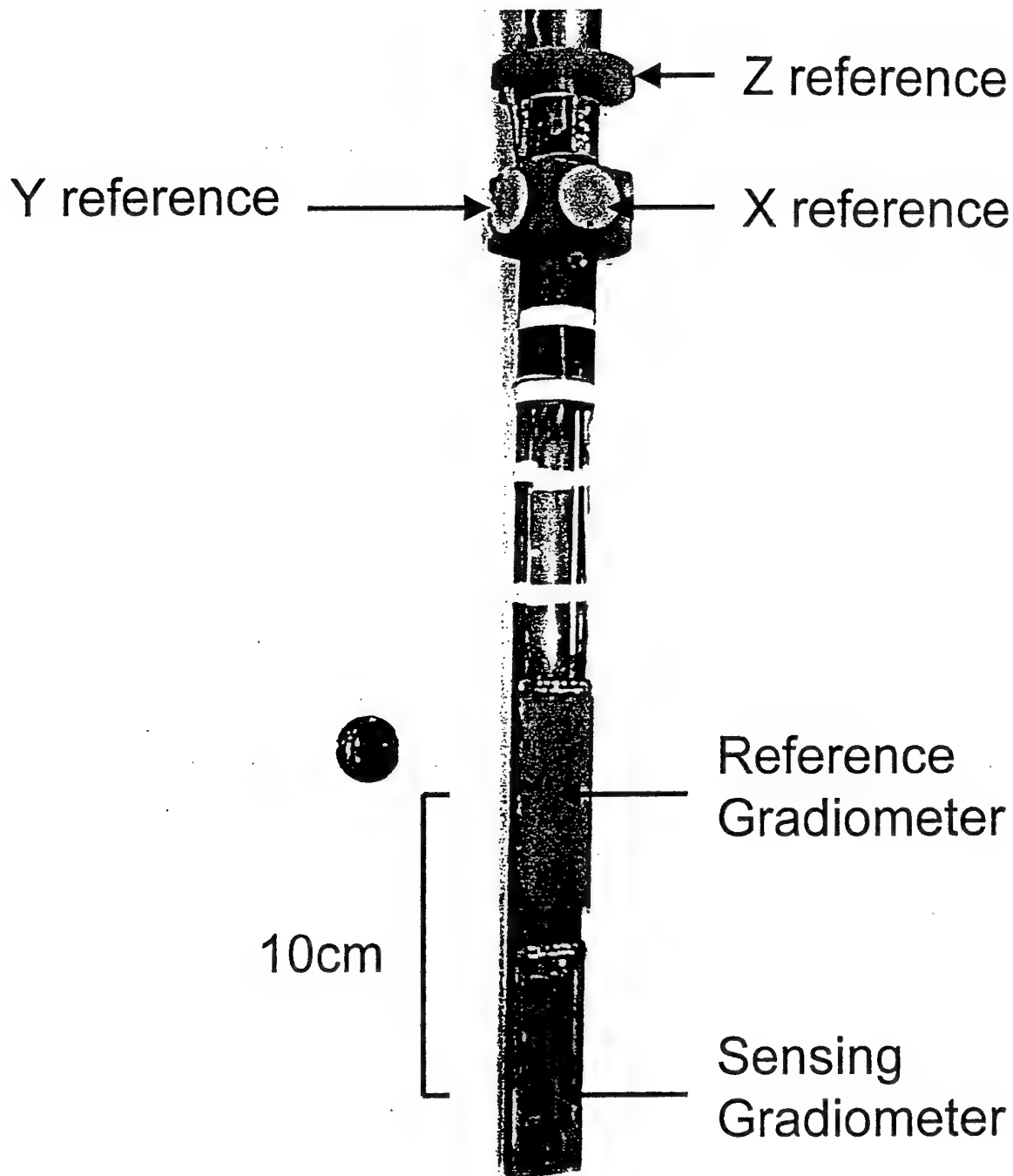


(b)

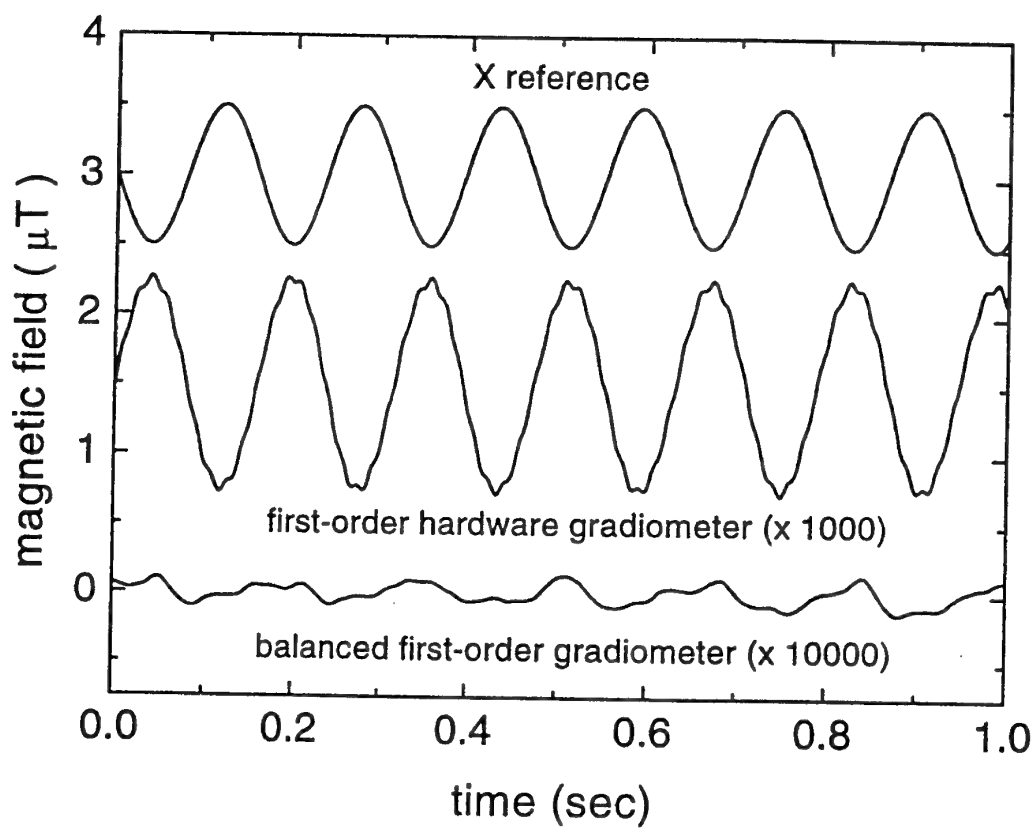


TYPICAL BALANCE 1:300

Probe with two gradiometers and three magnetometers

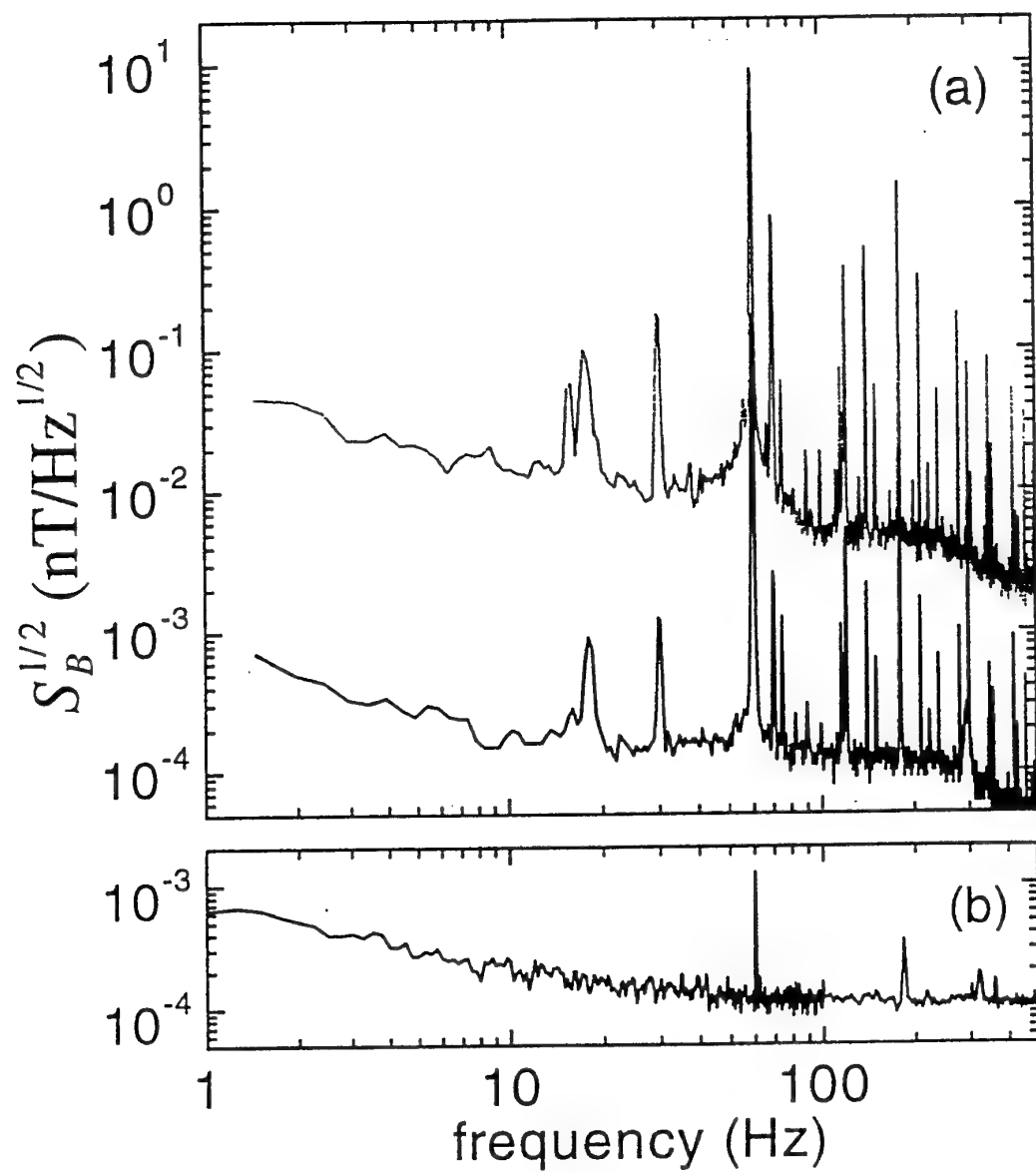


Balance of First-Order Gradiometer

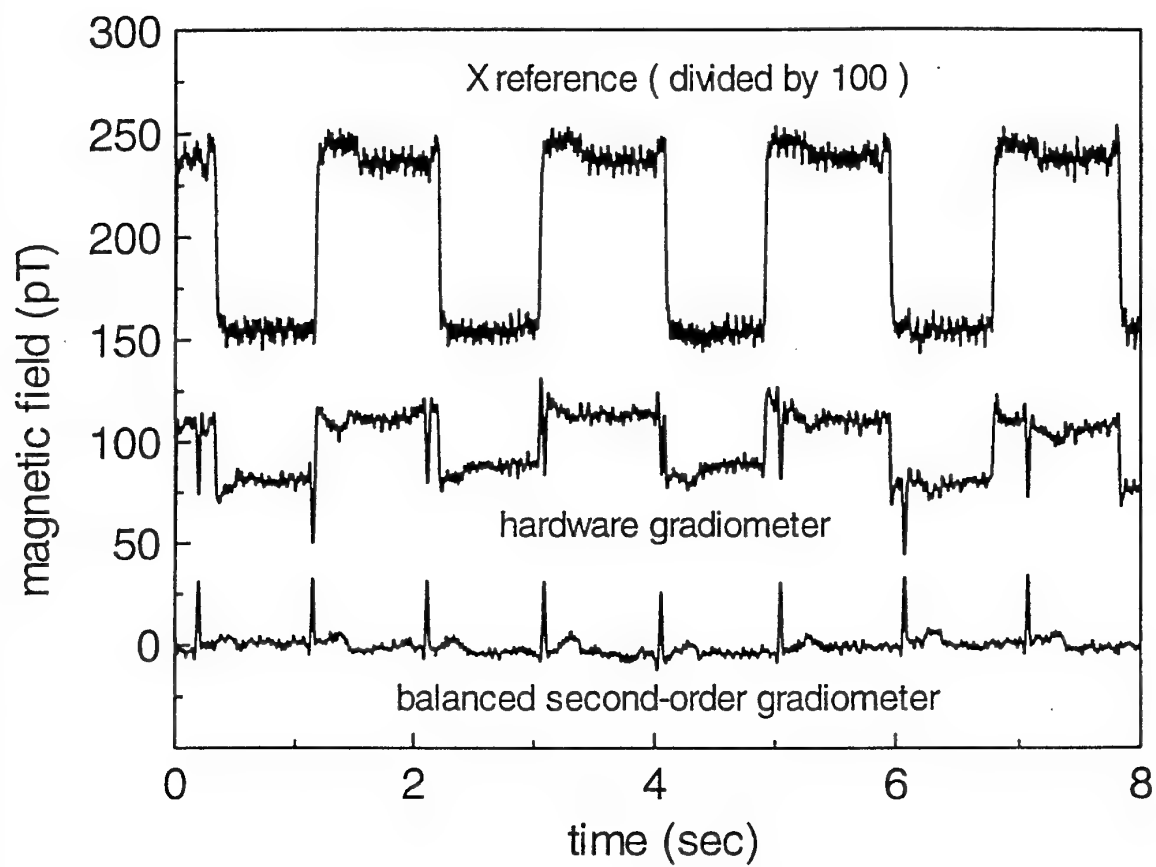


BALANCE : 20 ppm

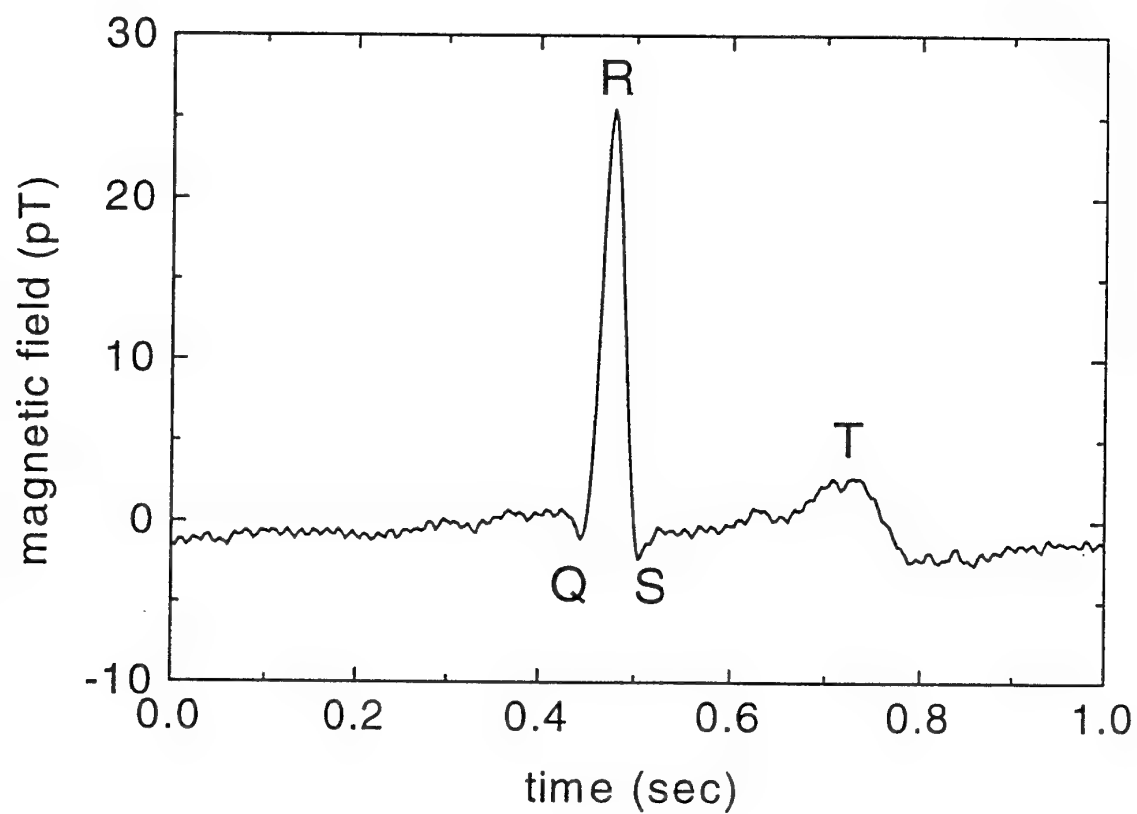
Noise Spectra of Magnetometer and Gradiometer



Magnetocardiogram in an Unshielded Environment



Magnetocardiogram in an Unshielded Environment (averaged 119 times)

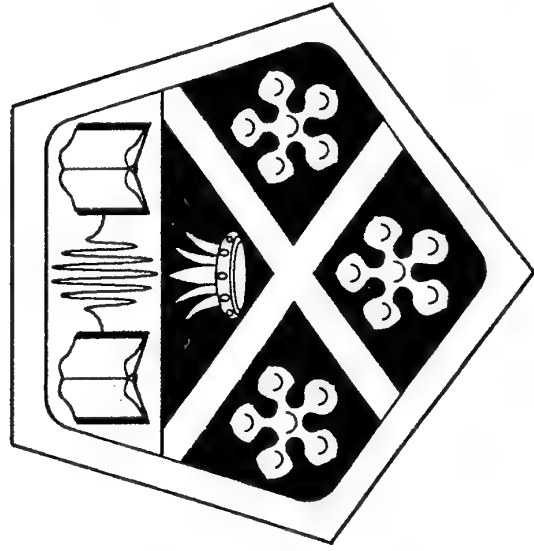


Frequency range of the dc SQUID

Magnetotactic bacteria: $\sim 10^{-3}$ Hz

Axion detector: ~ 1 GHz

Over 12 decades of frequency, appropriately used the dc SQUID is the most sensitive detector available.



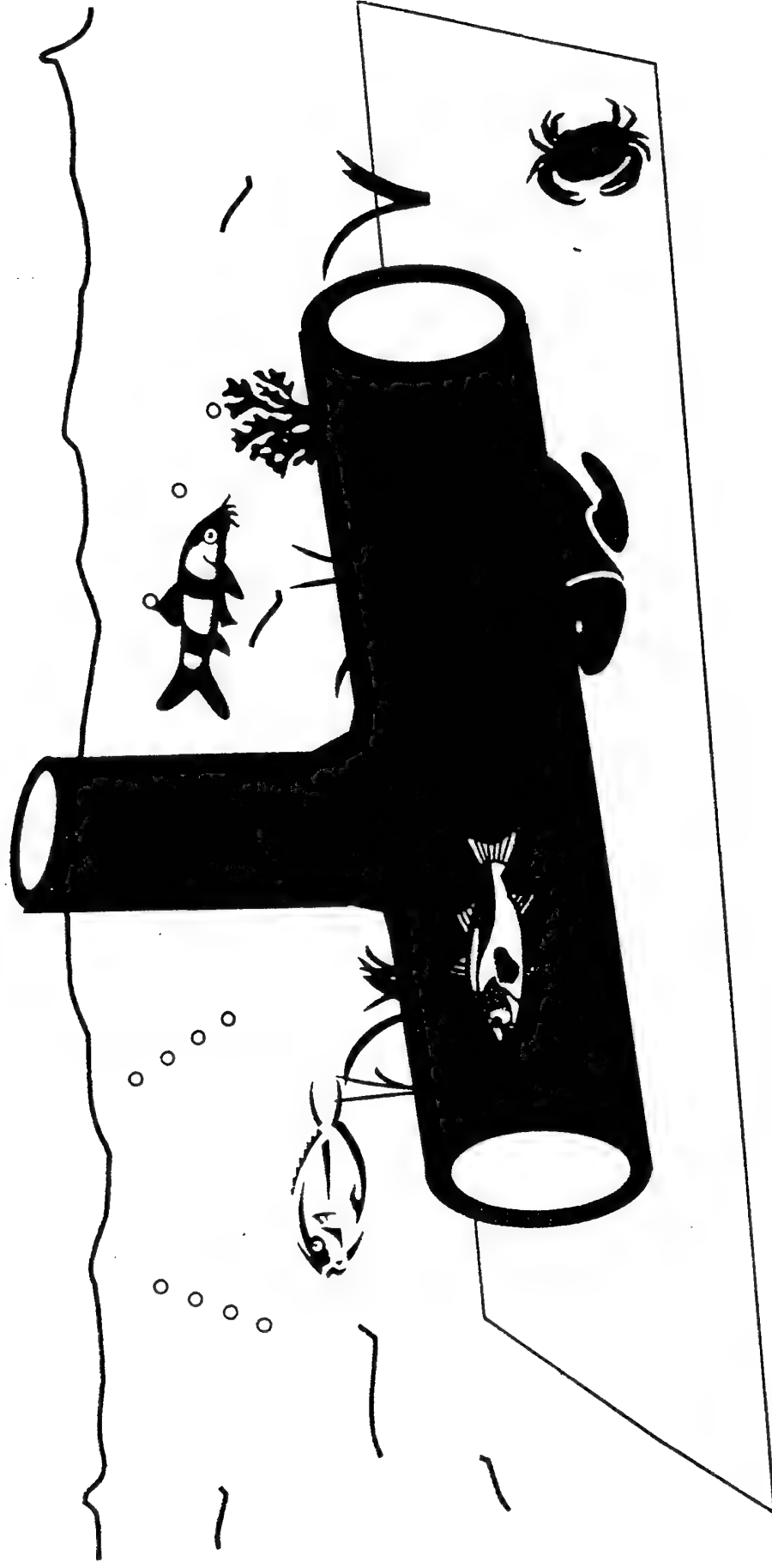
The Use of SQUIDs in the Non-Destructive Evaluation of Engineering Structures

Gordon B Donaldson
Department of Physics & Applied Physics
University of Strathclyde
Glasgow
Scotland



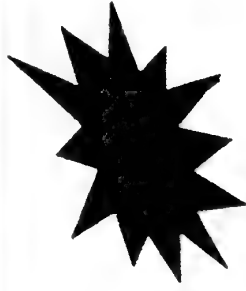
Harold Weinstock DHC, INSA Lyon 1999

North Sea Oil and Gas Pipes- Welds



Harold Weinstock DIC, INSA Lyon 1999

A Brief History of SQUID NDE



1985	'Buried' Gas Pipes	NRL/AFOSR
1987	'North Sea' Oil Pipelines AC injection and eddy current techniques	Strathclyde Vanderbilt
1988	Corrosion currents	MIT
1990	HTS	
1991..	Aircraft 'bodies' Concrete bridges Ageing in reactor steels Fish Inclusions in fine copper wire Stressed steels Microscope	SQM Hitachi Sumitomo ETL Maryland
..1998	Aircraft wheels Turbine blades	Julich FIT



Harold Weinstock DHC, INSA Lyon 1999

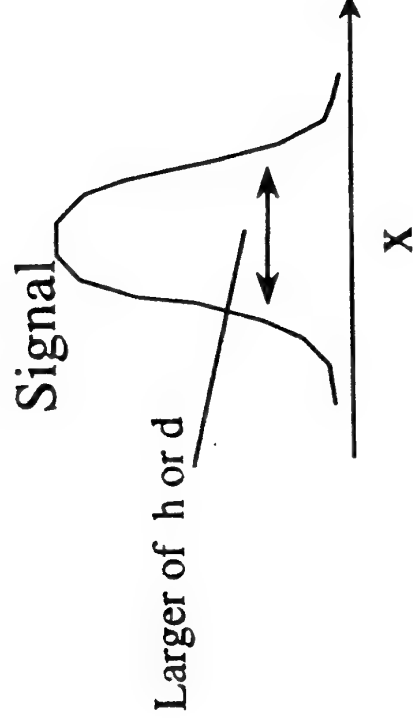
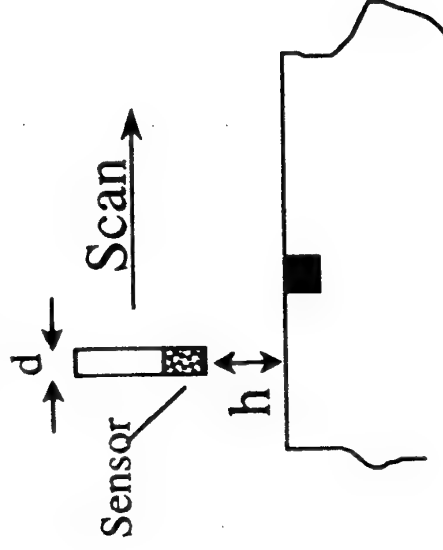
Magnetic Detection

Advantages

- Non-contacting- significant lift off possible
- Skin depth dependence allows probing

Disadvantages

- Can need large excitations
- No Time-of-flight or Phased array methods possible- spatial location comparable only to stand-off



Harold Weinstock DHC, INSA Lyon 1999

SQUIDS

Vector device

Gradiometer

Measures Φ , not $d\Phi/dt$ so useable to DC

In fact, measures $\Delta\Phi$ in large $\Phi_{\text{background}}$,
equivalent to 10^{-7}T in $4 \times 10^{-2}\text{T}$

Can use tiny pick-up coils to improve spatial resolution
(SQUID microscope)



Harold Weinstock DHC, INSA Lyon 1999

MAGNETIC SENSORS FOR NDE

Table 2: Magnetic sensors for eddy current NDE

Sensor	Sensor Package Size (Sensing Volume)	Spatial Resolution	Frequency Dependence	Signal Sensitivity	Cost
Induction coils	Small (1.5mm ϕ x 4mm)	Good	Signal \propto 1/f		Low (£'s)
Hall Sensors	Small (1mm ³)	Good	Good	Poor	Low (£'s)
Magnetoresistors	Medium (10mm ³)	Good	Good	Medium	High (£1k) ¹
Fluxgates	Medium (1mm ϕ x 15mm)	Medium	Good	Medium	High (£1k)
SQUIDs	High ² (1mm ² thin film)	Good	Good	Good	High (£1k) ³

¹Magnetoresistors are not widely available commercially. ²While the sensing area of a HTS SQUID is small, the size of the cryostat has to be taken into account. ³The initial outlay for a HTS SQUID is comparable to that of a fluxgate. Liquid nitrogen cryogen is inexpensive.

Why use SQUIDs?

- flaws in airframes at depths ~10-20mm require low noise at $f < 200\text{Hz}$ which only SQUIDs possess.
- low noise can also mean a much larger standoff compared to other sensors.
- often the cost of operating the SQUID is buried.

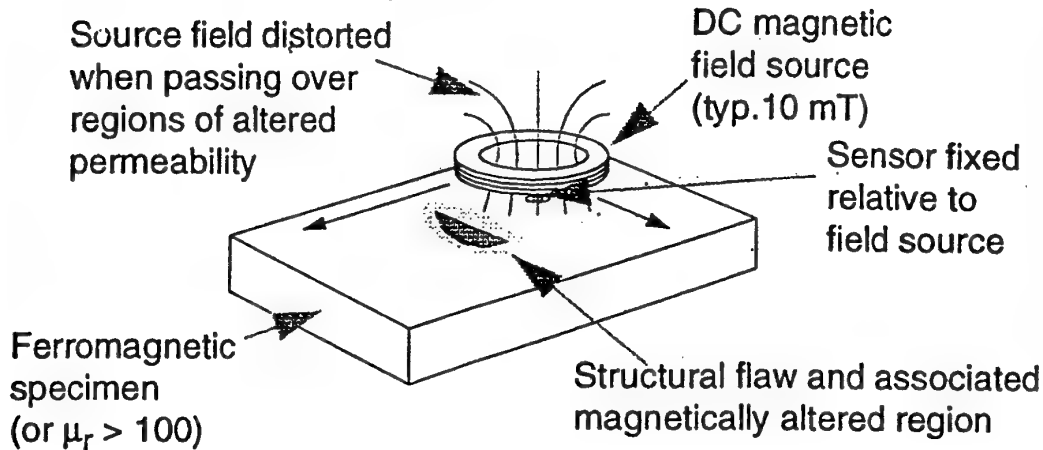
But

A £40K SQUID system is not state of the art technology. A fluxgate magnetometer detection system costing £40K is.

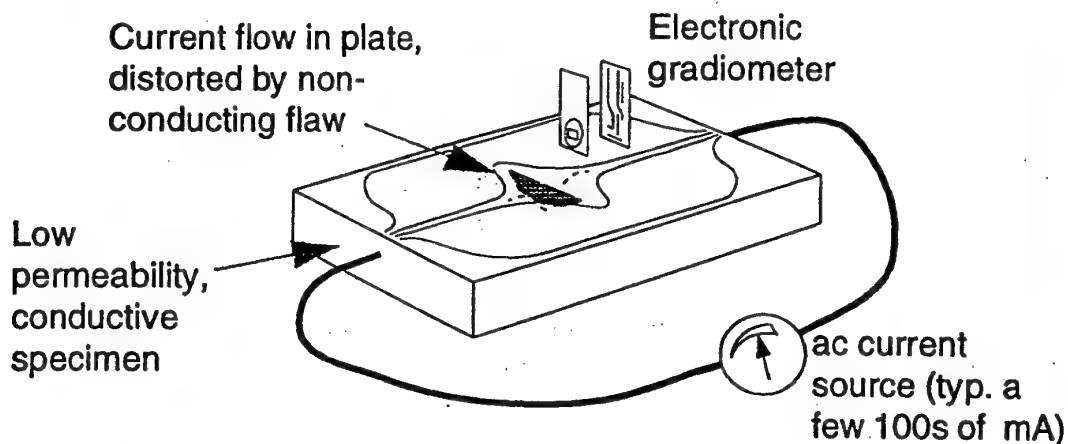
[General Reference — Jenks et al, "SQUIDs for Nondestructive Evaluation", Journal of Physics D: Applied Physics, vol. 30, pp. 293-323, 1997].

NDE Techniques

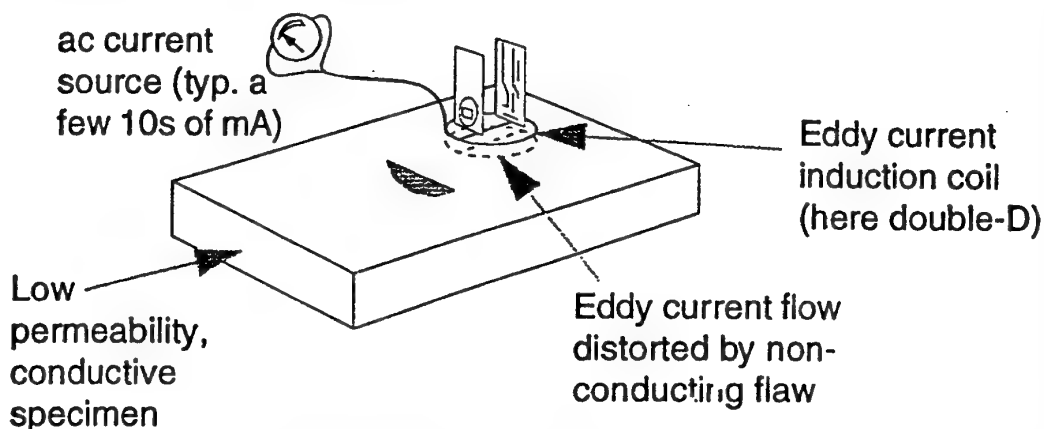
- Static field mapping



- Directly injected current mapping



- Eddy current measurement



5.2.1. Pipelines. In early work, Weinstock and Nisenoff [43] showed that when a 1 A, 4.6 Hz, current was passed along a metal pipe, the pipe could be accurately located using an axial SQUID gradiometer. A scan across the line of the pipe, given in Fig. 12, shows that when the pipe lies directly along the gradiometer axis there is a sharp zero in the detected signal, which is then purely transverse. The horizontal resolution here is rather better than the stand-off limit discussed earlier. Triangulation to determine the pipe position depends on a second scan with the gradiometer axis at about 30° to the vertical.

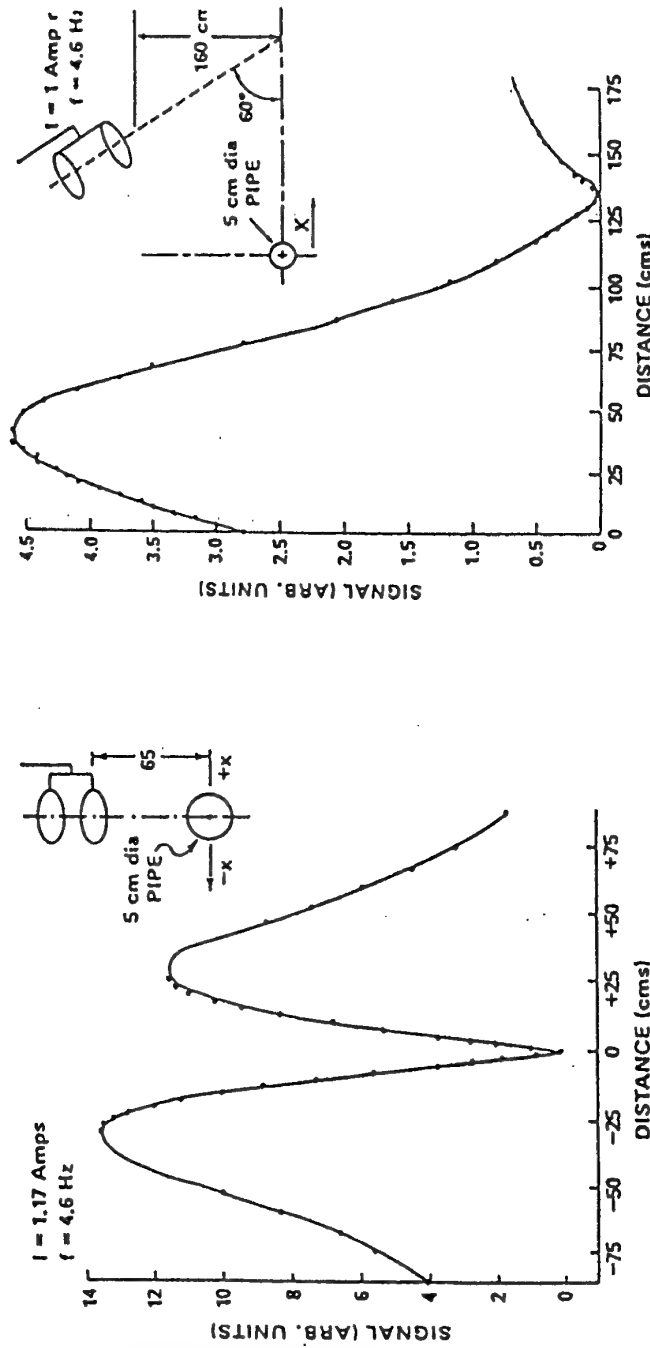
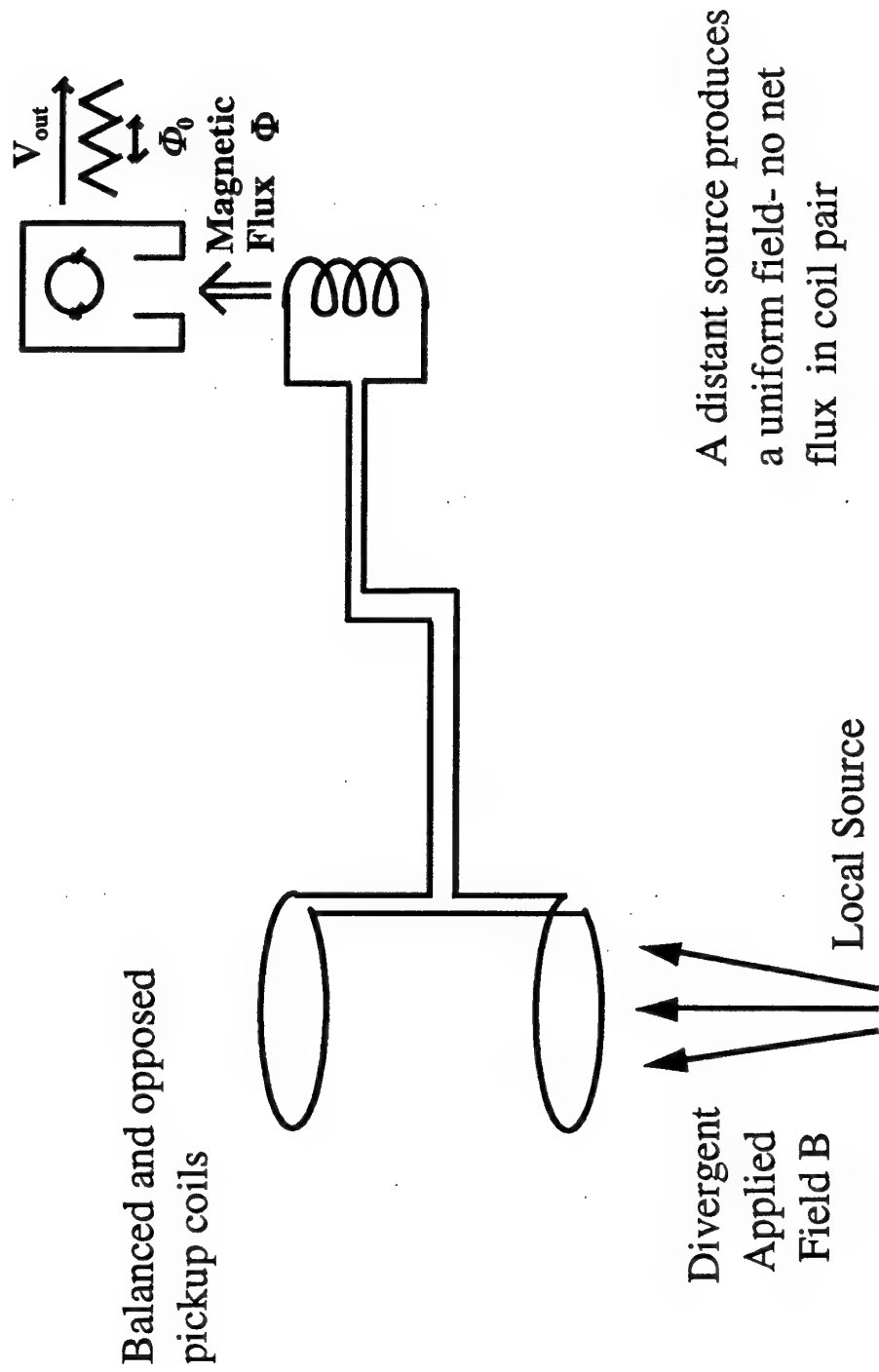


Figure 12. SQUID pipeline detection results [43].

Distances up to 1.6 m were studied, but much greater values should be possible and the method should be applicable to buried pipelines.

Holes and welds in the pipe could also be seen. They divert the flow of current, producing anomalies in the field measured by the SQUID as it is tracked along the line of the pipe.

SQUID Gradiometer



Harold Weinstock DHC, INSA Lyon 1999

110 SQUID (超電導量子干渉素子) センサによる 2 相ステンレス鋼の時効変化の検出 要旨

正 大 高 正 廣 (日立機械研) 正 長谷川 邦 夫 (日立機械研)
正 清 水 翼 (日立機械研) 正 高 久 和 夫 (日立日立)

S. Evanson (Univ. of Strathclyde)

G. B. Donaldson (Univ. of Strathclyde)

ルに置き、試験片が SQUID センサの下部を通

Table 1. Chemical composition and ferrite content of cast stainless steels

Material	C	Si	Mn	P	S	Cr	Ni	Mo	Co	N	Ferrite content (%)
A	0.016	1.36	0.16	0.014	0.005	19.4	10.05	2.21	0.03	—	12.5
B	0.01	1.25	0.63	0.010	0.006	20.30	9.54	2.14	0.03	0.04	21.3
C	0.02	1.39	0.59	0.018	0.006	20.74	9.67	2.30	0.04	0.03	26.1

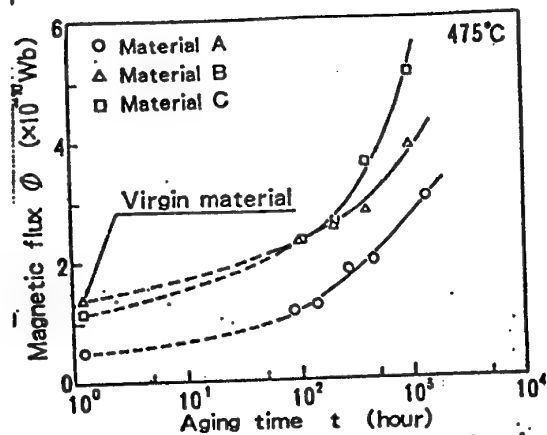


Fig. 3 Intensity of SQUID sensor as a function of aging time

ル方向が反転するためである。また、SQUID セ

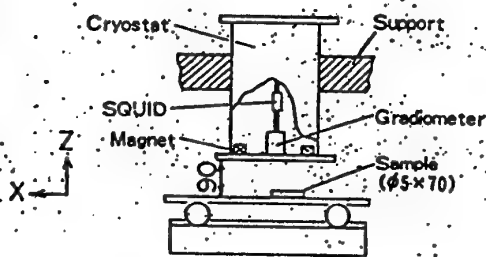


Fig. 1 Schematic of experimental apparatus

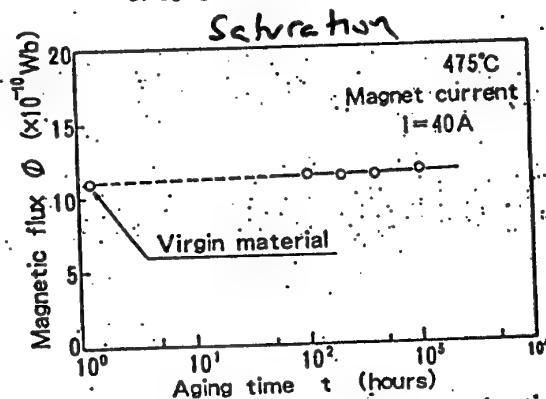


Fig. 4 Intensity of SQUID sensor as a function of aging time (Material C)

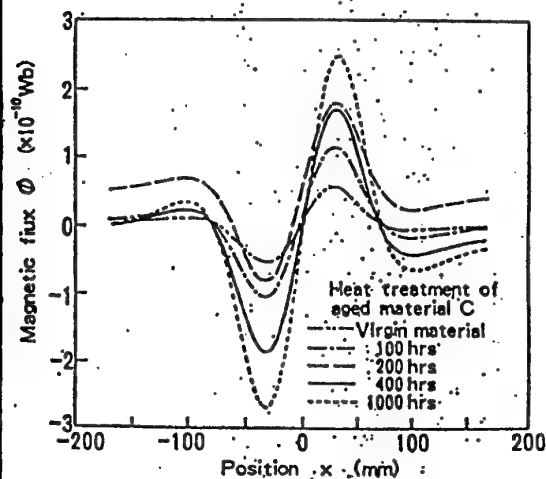


Fig. 2 Intensity of SQUID sensor

Remanence

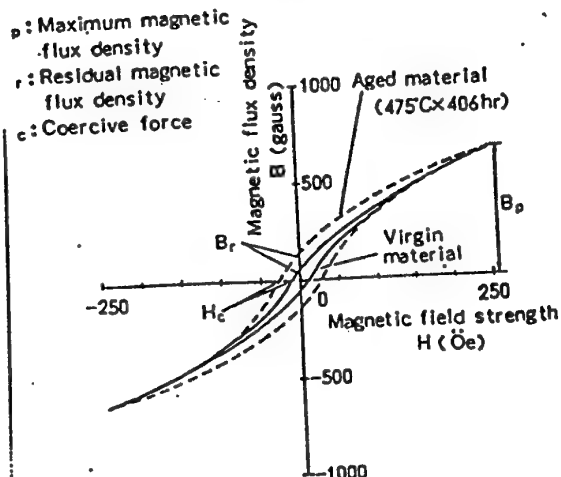


Fig. 5 Magnetization characteristics of virgin and aged cast stainless steel (Material C)

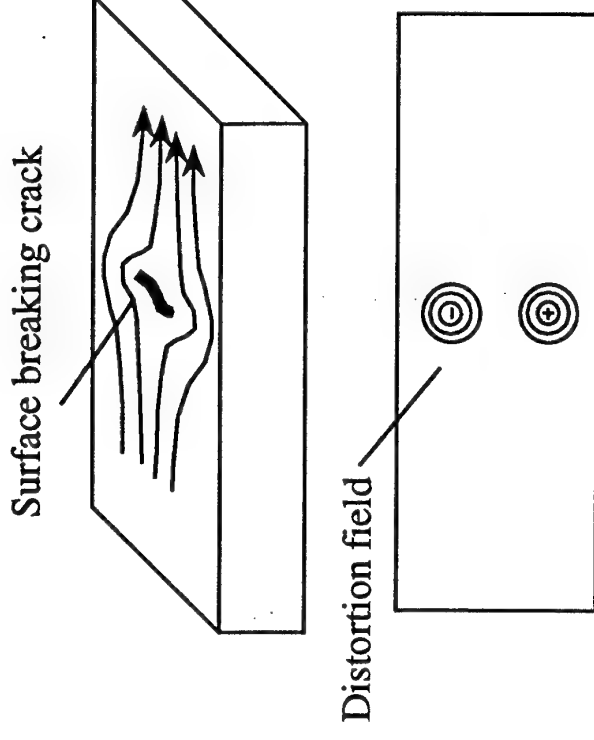
Magnetic

Remote Magnetometry

- Measure spontaneous fields of magnetised inclusions
- Measure induced fields of magnetisable inclusions
- Measure effective difference dipoles of inclusions of permeability different ($\Delta\mu$) from host (including void $\mu=0$)
- Measure diverted fields
- Measure flux leakage

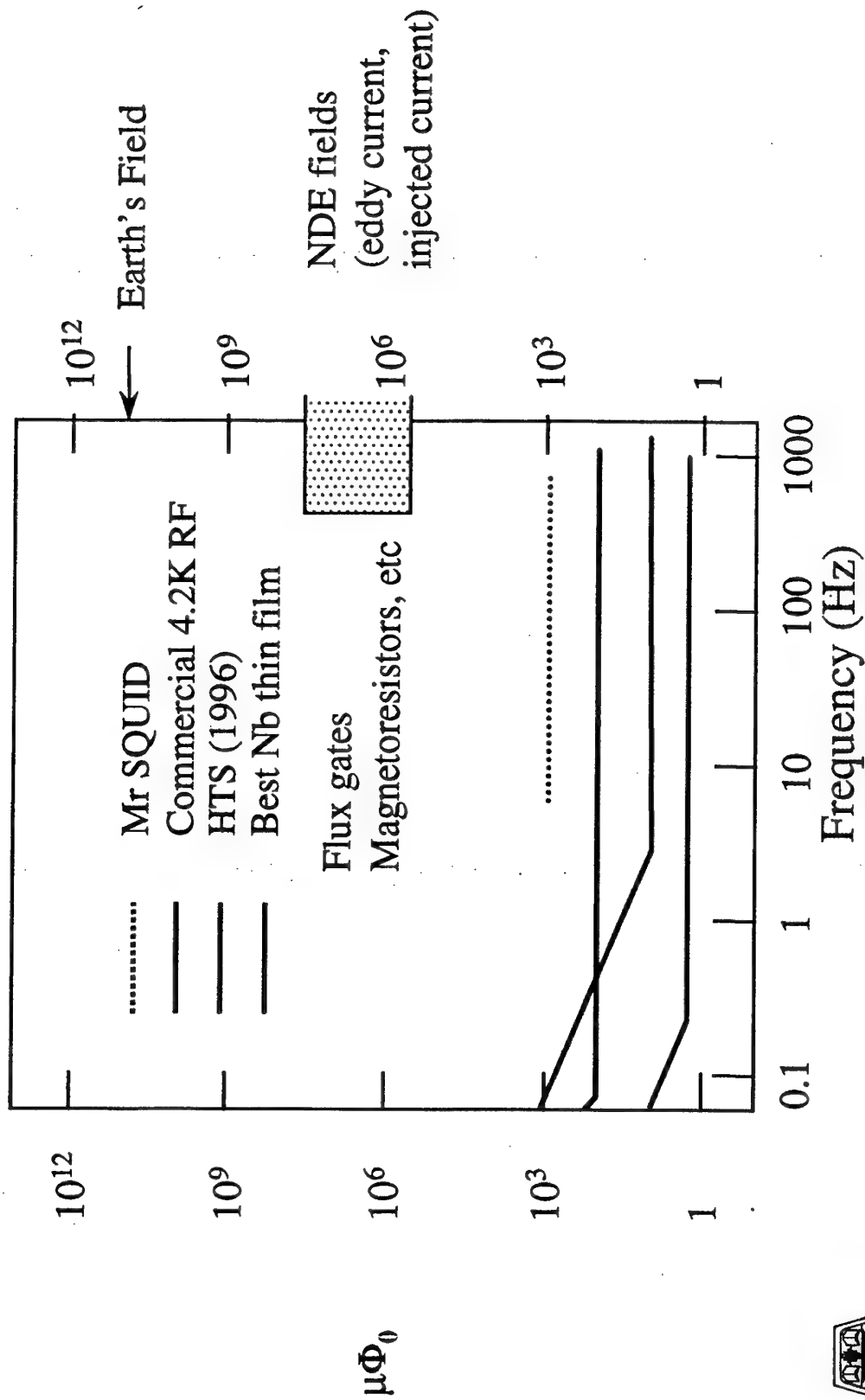
Remote Galvanometry

- Measure difference fields caused by distorted flow of injected or induced (eddy) currents, close to flaw
- Measure fields due to noise currents



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Non-Destructive Evaluation (NDE)

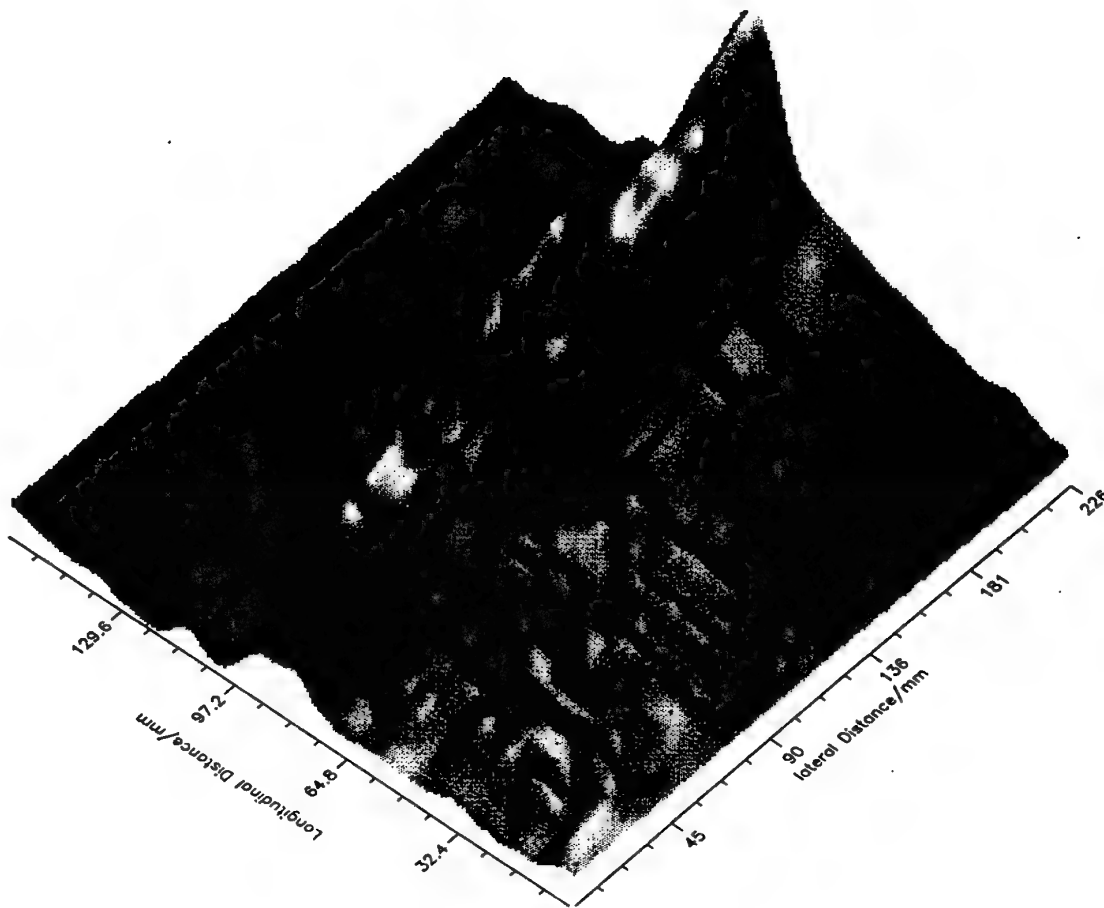


Harold Weinstock DHC, INSA Lyon 1999



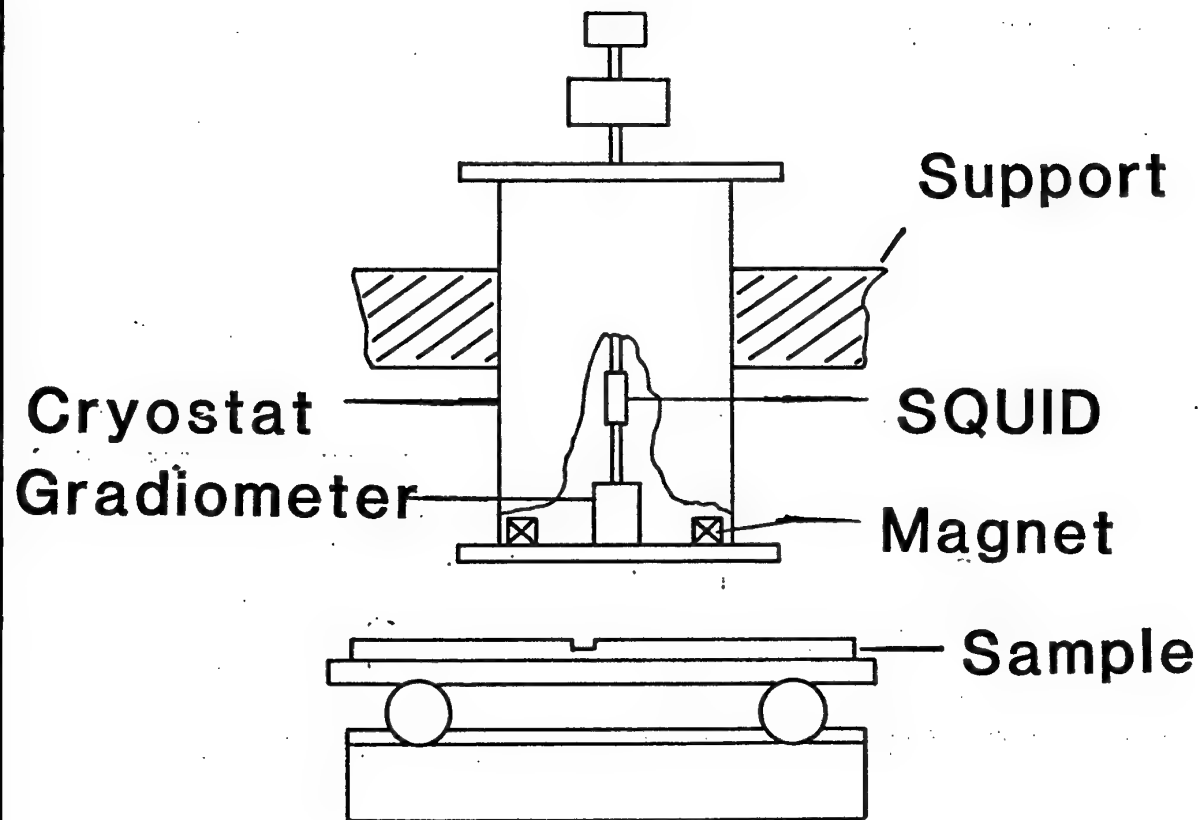
STATIC FIELD MAPPING AND MATERIAL CHARACTERISATION

A MILD STEEL PLATE WAS ARTIFICIALLY CRACKED BY CYCLIC THREE-POINT LOADING AND WAS SCANNED BENEATH A LOW TEMPERATURE SQUID SENSOR. NO CONTACT WITH THE STEEL PLATE WAS MADE. THE CRACK WAS DETECTED BY MEASURING APPLIED FIELD DISTORTIONS CAUSED BY ASSOCIATED MAGNETIC PERMEABILITY VARIATIONS.



THIS TECHNIQUE HAS BEEN HIGHLY SUCCESSFUL FOR PREDICTING POSSIBLE CRACK SITES, EVEN THROUGH A THICK LAYER OF NON-MAGNETIC MATERIAL.

Experimental Apparatus



'Room temperature' application

Planar gradiometers

Heavy ~~use~~ use of computer data
acquisition and processing

Non-Destructive Evaluation (NDE)

Corrosion and embrittlement in

- Chemical and nuclear reactors
- Pipelines (especially coated, sub-sea, etc.)
- Ageing aircraft

are major, and expensive problems.

E.g.

- Extension of KC135 (Boeing 707), now 35 years old to 70 year life
- Japanese reactor accident



Harold Weinstock DHC, INSA Lyon 1999

CURRENT FLOW \leftrightarrow MAGNETIC FIELD TRANSFORMATIONS

STARTING WITH THE BIOT-SAVART LAW:

$$\underline{B}(\underline{r}) = \frac{\mu_0}{4\pi} \int \frac{\underline{J}(\underline{r}') \times (\underline{r} - \underline{r}')}{|\underline{r} - \underline{r}'|^3} d^3 \underline{r}'$$

EXTRACTING THE VERTICAL COMPONENT AND EXPRESSING IN TERMS OF GREEN'S FUNCTIONS GIVES:

$$B_z(\underline{r}) = J_x(x, y) \otimes G_y(x, y, z) + J_y(x, y) \otimes G_x(x, y, z)$$

THE TWO GREEN'S FUNCTIONS ARE:

$$G_x(x, y, z) = \frac{\mu_0 dz}{4\pi} \left[\frac{x}{(x^2 + y^2 + z^2)^{3/2}} \right]$$

AND

$$G_y(x, y, z) = \frac{\mu_0 dz}{4\pi} \left[\frac{y}{(x^2 + y^2 + z^2)^{3/2}} \right]$$

TRANSFORMING INTO FREQUENCY SPACE AND APPLYING THE LAW OF CONTINUITY, GIVES A SIMPLE TRANSFORM BETWEEN CURRENT DENSITY AND MAGNETIC FIELD:

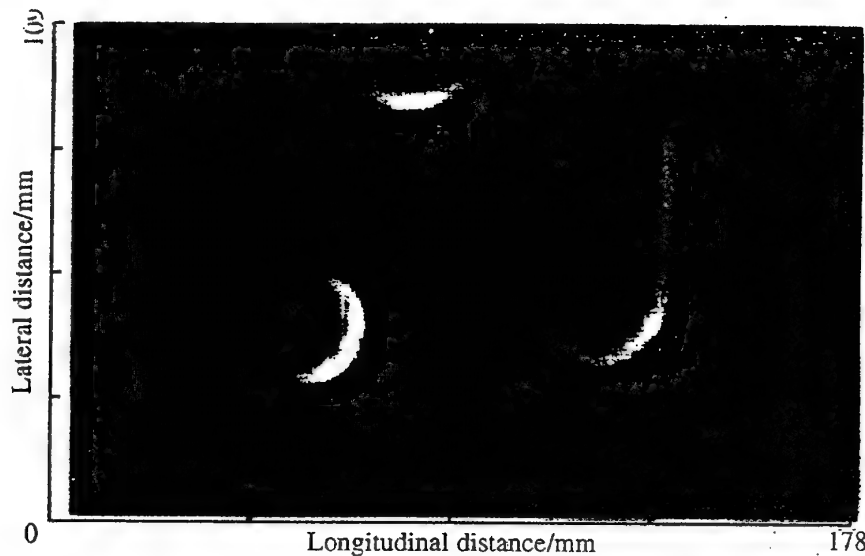
$$b_z(k_x, k_y, z) = i \frac{\mu_0 d}{2} \frac{k}{k_y} e^{-kz} j_x(k_x, k_y)$$

BY REARRANGEMENT THE INVERSE IS GIVEN BY:

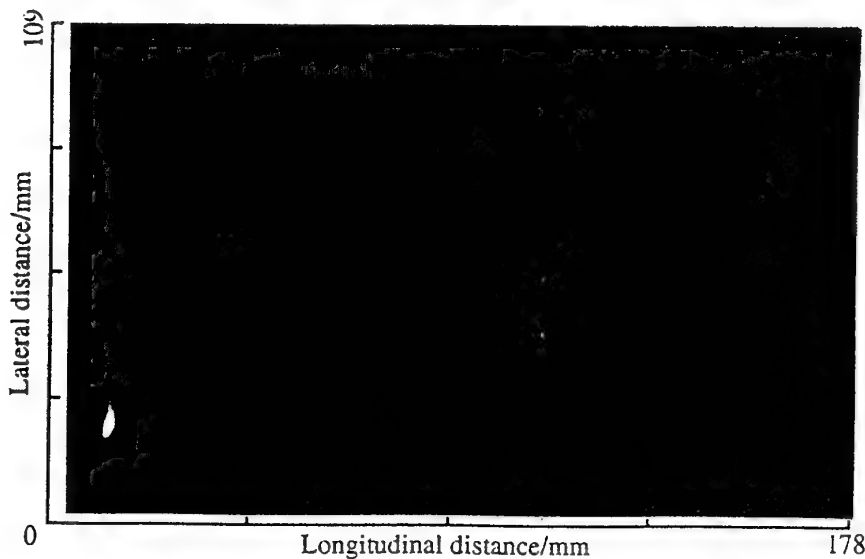
$$j_x(k_x, k_y) = -i \frac{2}{\mu_0 d} \frac{k_y}{k} e^{kz} b_z(k_x, k_y, z)$$

AN EXAMPLE OF MAGNETIC FIELD TO CURRENT FLOW TRANSFORMATIONS

A PRINTED CIRCUIT BOARD IN THE SHAPE OF AN SU WITH A SMALL CURRENT FLOWING IN IT. WAS SCANNED BENEATH A LOW TEMPERATURE SQUID SENSOR. PRODUCING A MAGNETIC FIELD MAP AS SHOWN BELOW:



BY USING THE ALGORITHM DESCRIBED ABOVE THE CURRENT DENSITY WAS CALCULATED FROM THE Z COMPONENT OF THE MAGNETIC FIELD:



VARIATIONS IN PCB TRACK WIDTH AND THE SOLDER TAGS CAN EASILY BE RESOLVED.

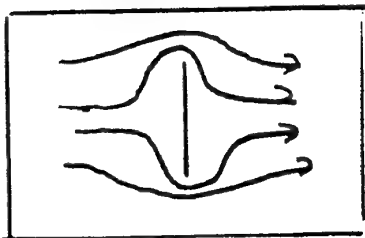
Depth profiling by frequency scanning

$$\delta = \sqrt{\frac{\rho}{\mu\mu_0\pi f}} = \sqrt{\frac{1}{\mu\mu_0\sigma\pi f}} = \frac{10^6}{2\pi} \sqrt{\frac{10}{\mu\sigma f}} \text{ mm}$$

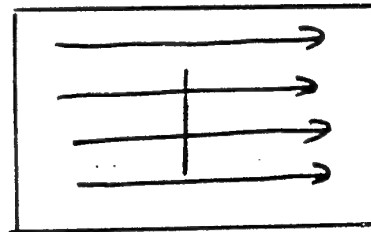
Material parameter	Cu	Al	NiCr	Stainless steel	Mild steel	Si steel	Graphite
ρ ($\times 10^{-8}$) Ωm	1.8	2.7	103	43	10	43	1000
μ	1	1	1	1	800	50,000	1
Frequency	Skin depth (mm)						
1 Hz	67	83	510	330	5.6	1.4	1591
100 Hz	6.7	8.3	51	33	0.56	0.14	159
10 kHz	0.67	0.83	5.1	3.3	0.056	0.014	15.9
1 MHz	0.067	0.083	0.51	0.33	0.0056		1.59

For crack depth \pm

$\delta \ll t$



$\delta \gg t$



$\delta \downarrow$
 \uparrow



$\delta \downarrow$
 \uparrow



$\delta \downarrow$
 \uparrow

Depth averaged current

Experimental procedure

Many AC techniques generate single frequency 1D or 2D scans of a specimen. In contrast, we make measurements over a range of frequencies:

- $s(f)$ at a signal position, near the slot.
- $r(f)$ at a reference position, above a plain piece of plate, far from the slot.

Then we normalise, calculating $s(f)/r(f)$, which contains depth information via the skin effect.

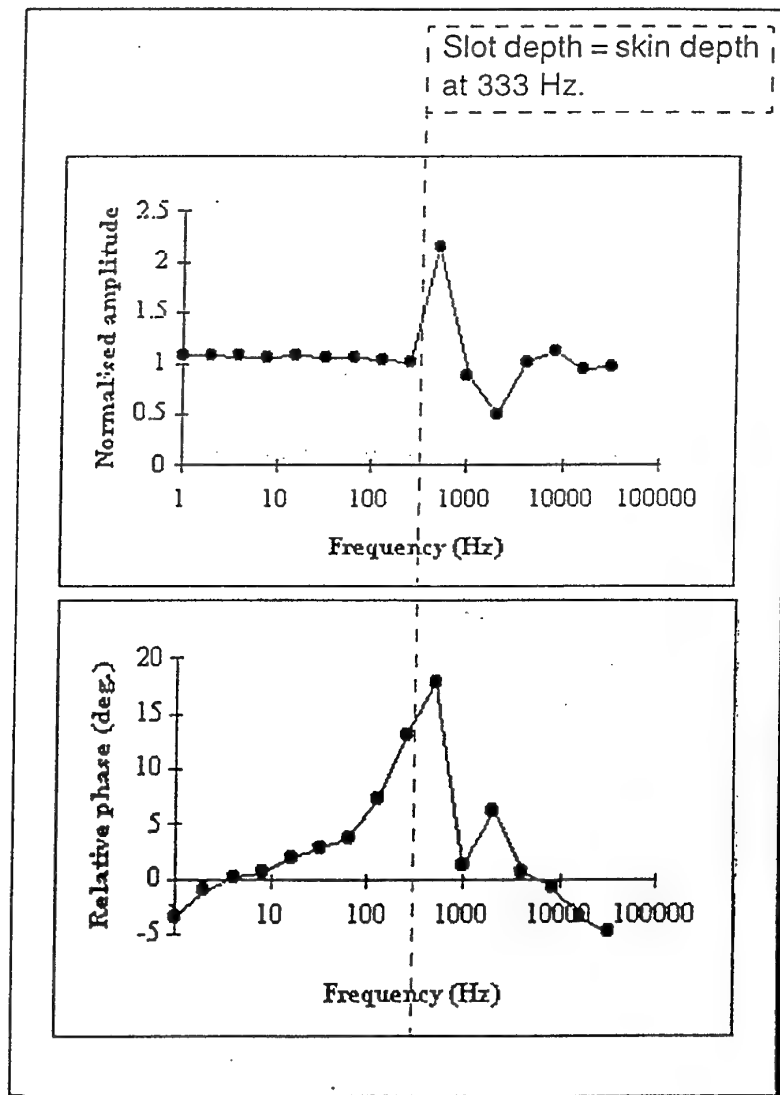
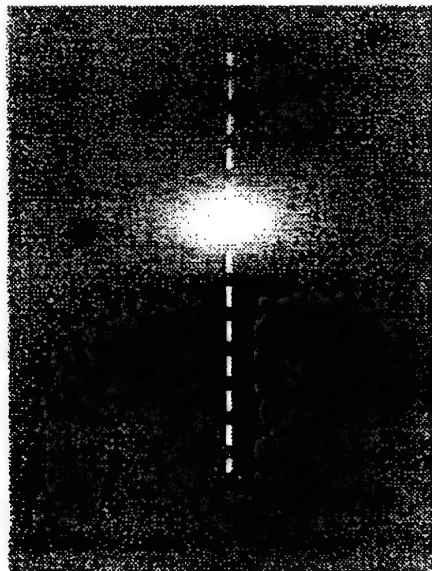
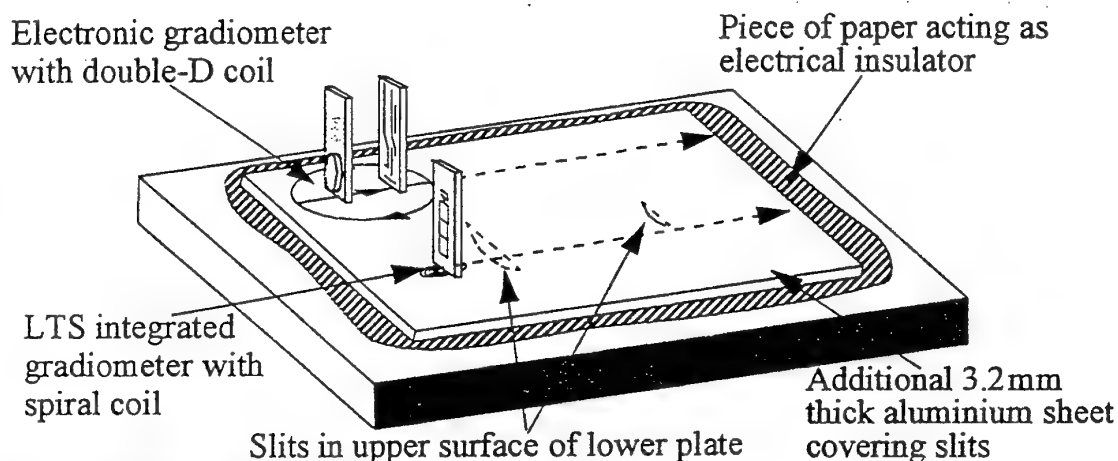


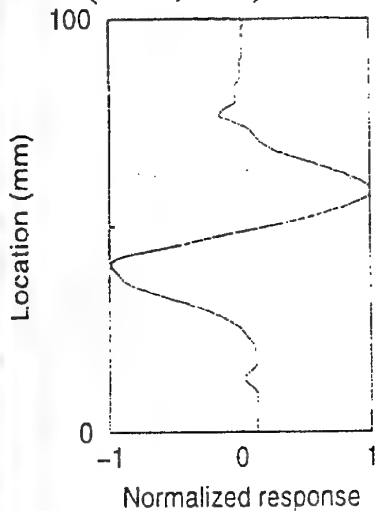
Figure 3: a typical experimental result, for a subsurface slot 6.5 mm deep.

NDE WITH LTS SQUID GRADIOMETERS

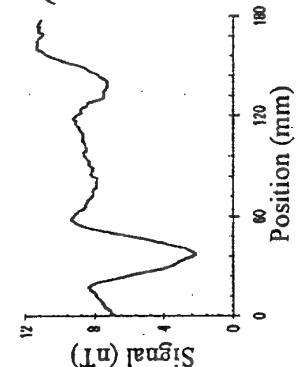
Uses same scanning system and electronics, but the requirement of a LHe cryostat imposes an additional standoff between the sensor and the sample. (Varying the coil to sample liftoff is much more critical).



LTS (70Hz, 0.5A)



HTS (570Hz, 0.05A)
SQUIDS in motion



- LTS Gradiometers are overly sensitive for NDE purposes.
- rf or magnetic shielding is often required for operation in a magnetically hostile environment.
- The design and application of higher order asymmetric gradiometers *may* have some future in very specialised areas.

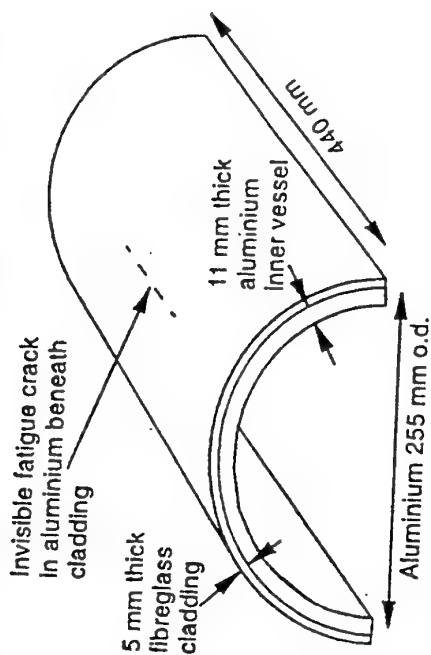
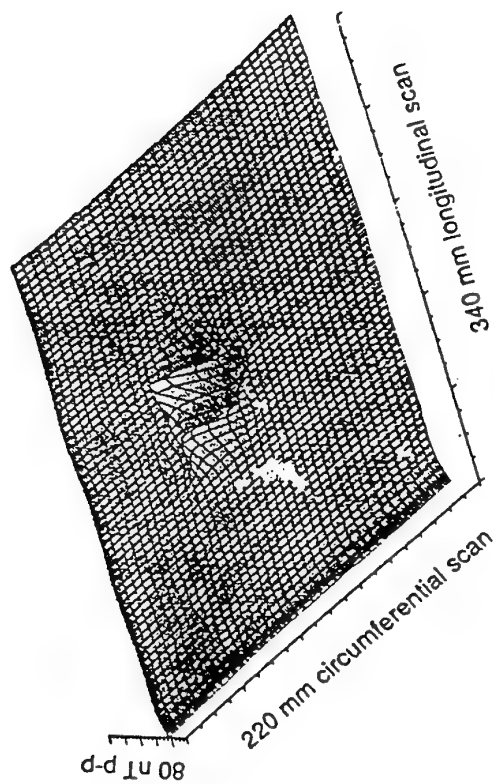


Figure 22. Section of fibreglass-clad aluminium pressure vessel with a fatigue through crack in its metal wall (supplied by British Gas).



Section 2.1.1.B). The concentration and charge gradients force Na^+ into the cell and if the

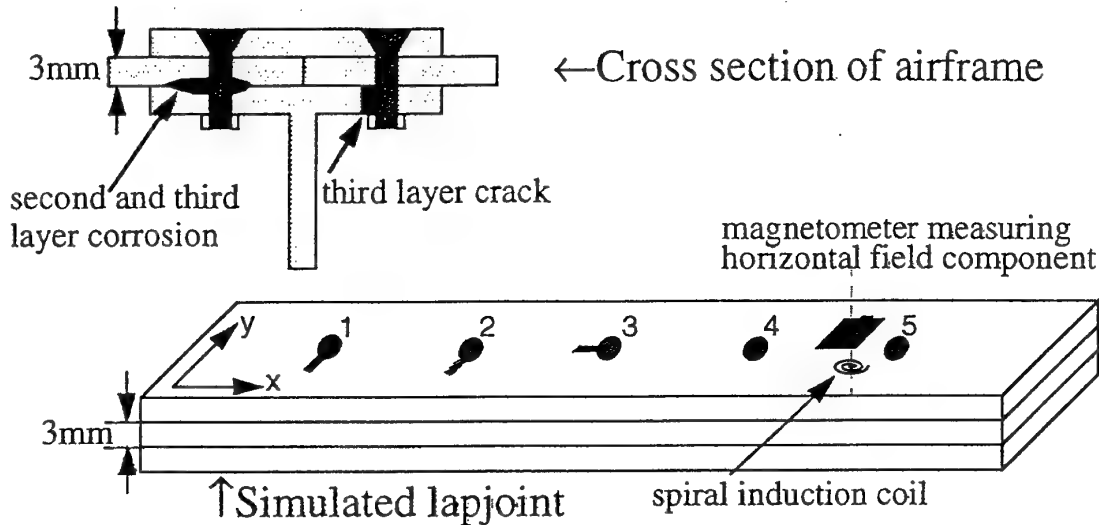
Figure 2.7 Post-synaptic synapse. Neurotransmitters are released into the synaptic cleft and recombine with the post-synaptic membrane. The recombination of excitatory neurotransmitters, force a change in the permeability of the membrane to Na^+ ions which initiates depolarisation. (Gaudin and Jones, 1989).

threshold potential is reached an action potential is initiated in the post-synaptic neurone. The action potential can now propagate along this new neurone. The current distribution of a post-synaptic potential is like that of a single current dipole. The measured biomagnetic signal is not of one axon synapsing with another but is the sum of the magnetic field from many synapses in the nerve bundle.

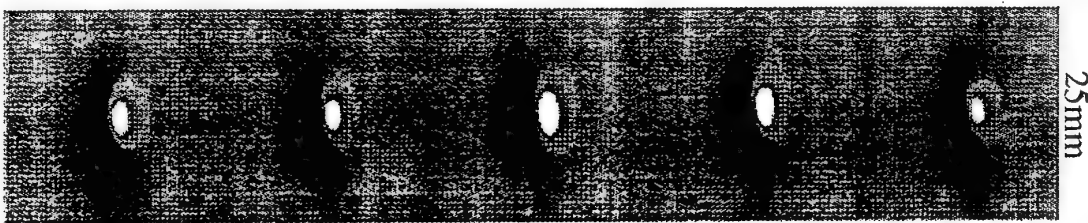
The post-synaptic potential always occurs at the synapse at the same time for a given nerve and stimulus site. The recordings taken from the spinal cord and cortex in Chapter 6 and 7 are of the magnetic fields induced by post-synaptic potential currents of several hundred neurones. Stimulation of the median nerve at the wrist, causes propagation of an action potential along the nerve bundle to the post-synaptic neurones in the dorsal horn in the spinal cord, 14ms after the stimulation. The signal

MULTILAYER SPECIMENS

Realistic aircraft lap-joint structures may have flaws beside fasteners in the first, second or even third layers, ie flaws hidden below 6mm of aluminium. The lack of any sealant between the layers makes ultrasonic testing unsuitable.



Eddy currents induced in the sample using a spiral coil located on the cryostat tail. $I_{coil} \sim 0.5A$, $f_{coil} = 620Hz$. The HTS SQUID magnetometer is scanned across the sample at $v \sim 3mm s^{-1}$ and takes 60mins to collect the data.

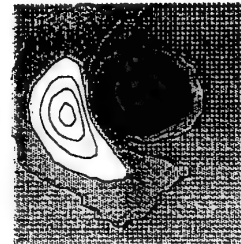


The flaw signal is superimposed onto the rivet signal and identical unflawed rivets do not have identical signatures due to the nature of the contact between the rivet and the plate.



620Hz

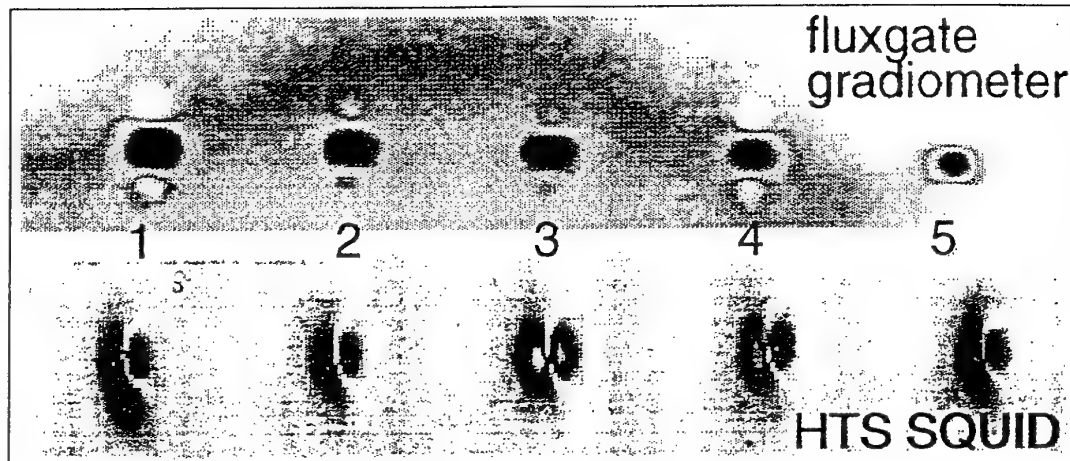
Deeper flaws \rightarrow lower excitation frequency
Reducing the frequency to 170Hz increases the flaw signal at rivet 2. Use digital signal subtraction to remove the rivet signal from the image.



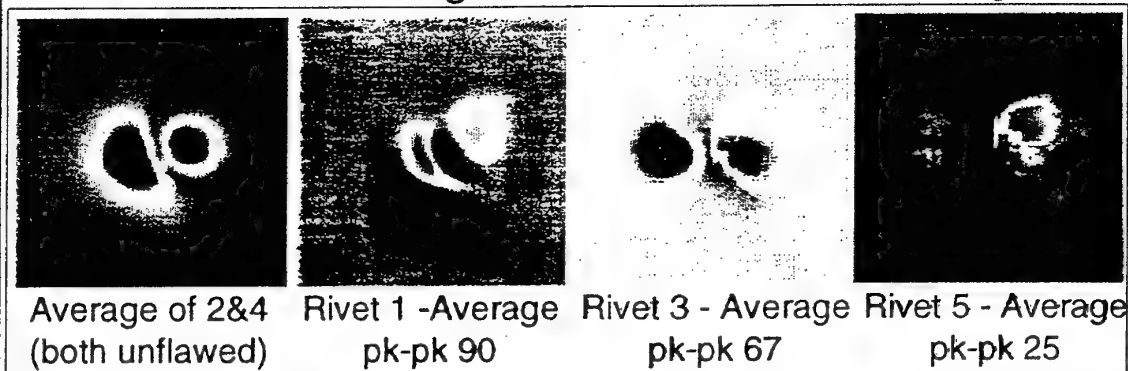
170Hz

FLUXGATES vs SQUIDS

Both sensors were used to map the features of the lap-joint sample, starting with the top layer.



Two-dimensional cross-correlation of the final image with an "ideal, unflawed fastener" can be used to isolate the flaw signal. For the SQUID image:



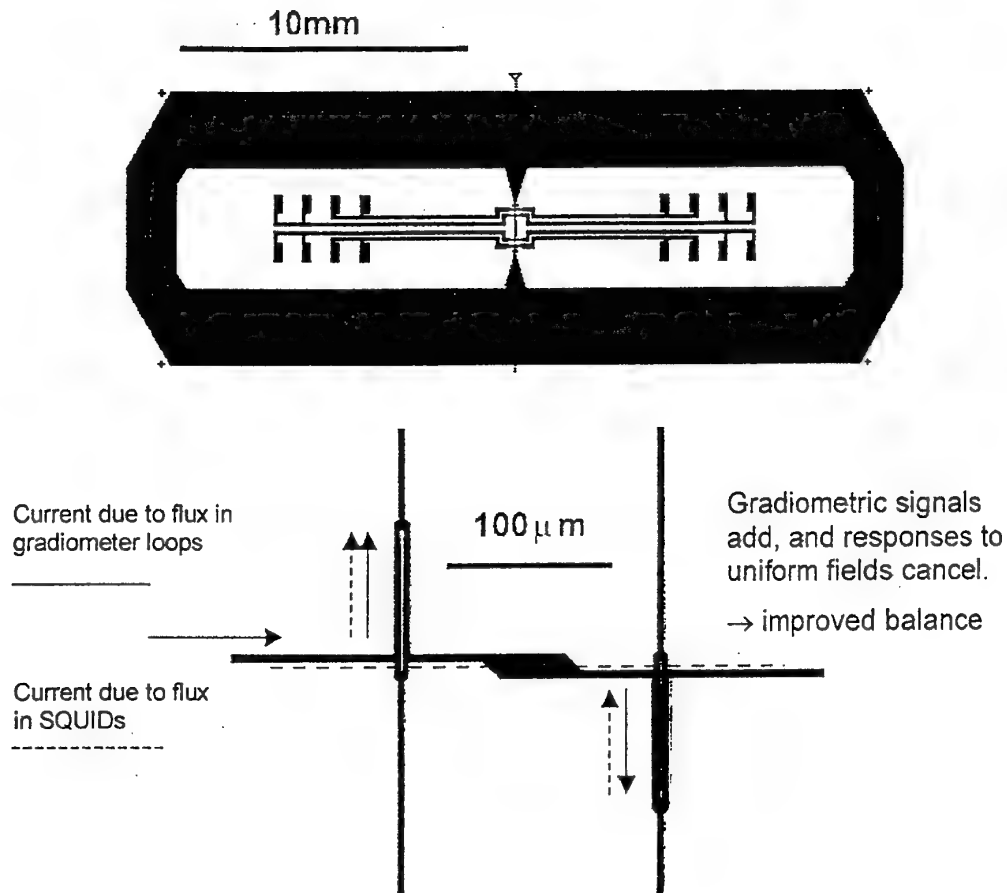
In the above example, a moderately low noise HTS SQUID performs better than a fluxgate in terms of spatial and signal resolution.

Removal of the rivet signal can also be performed using orthogonal induction of the eddy currents.

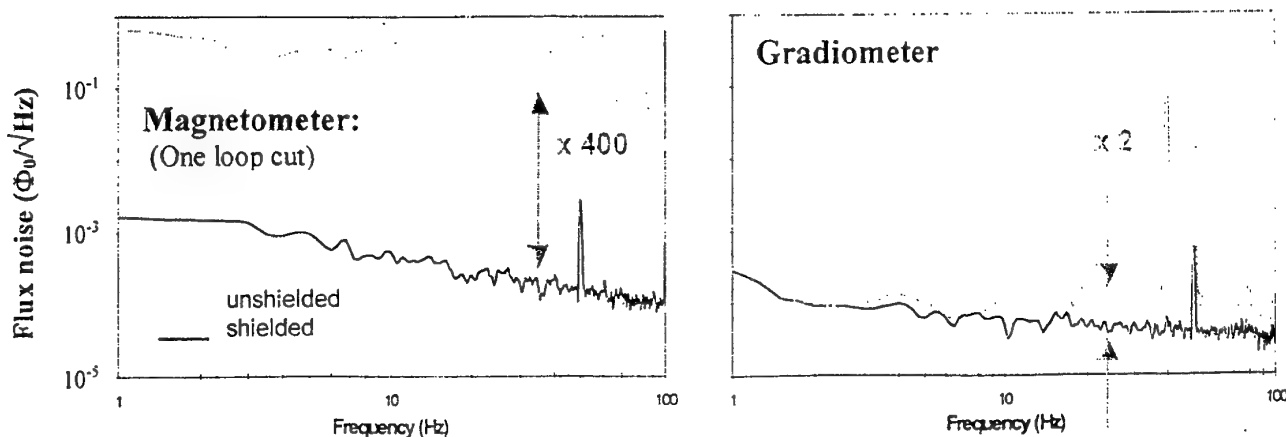
Second generation gradiometers

Aimed at ultra low-noise applications:

- Fabricate gradiometer on large substrate $30 \times 10 \text{ mm}^2$ --> baseline is 14mm.
- Improve inductance matching between gradiometer loop and SQUID
- Use novel coupling scheme where two SQUIDs are connected to gradiometer loops to compensate for parasitic effective area.



First Tests: Gradient resolution is $222 \frac{\text{fT}}{\text{cm}/\text{Hz}}$ --> suitable for biomagnetism
 Gradiometer operates well unshielded



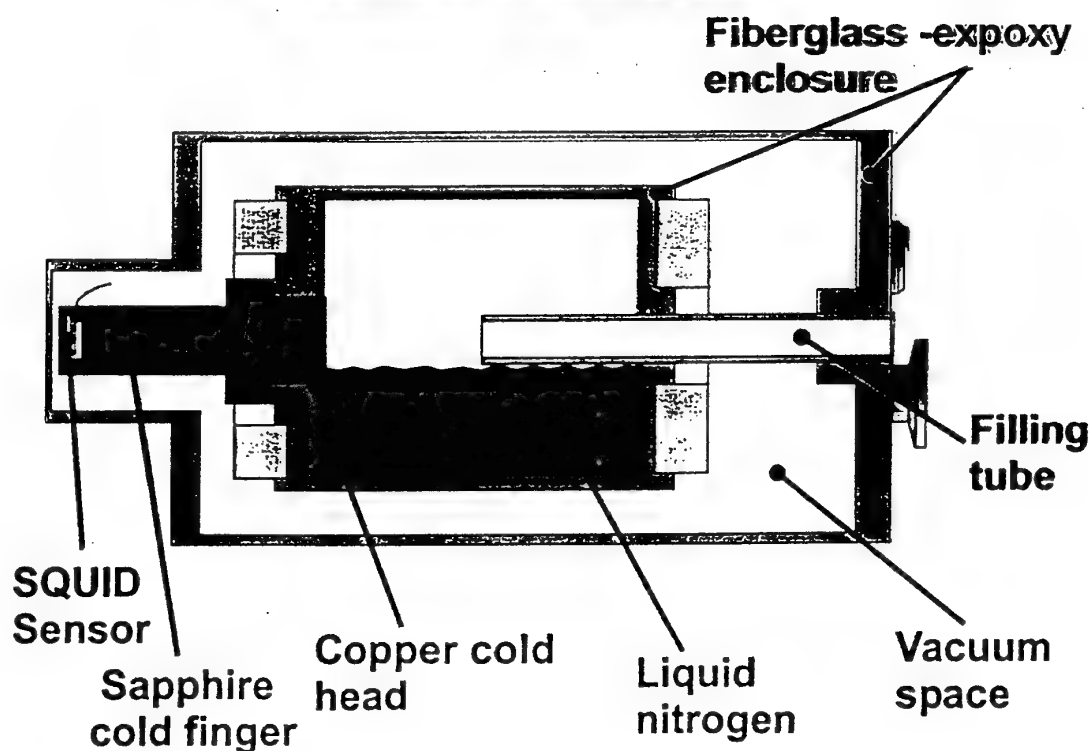


4) Mobile Cryostat with SQUID and Scanmaster moving unit





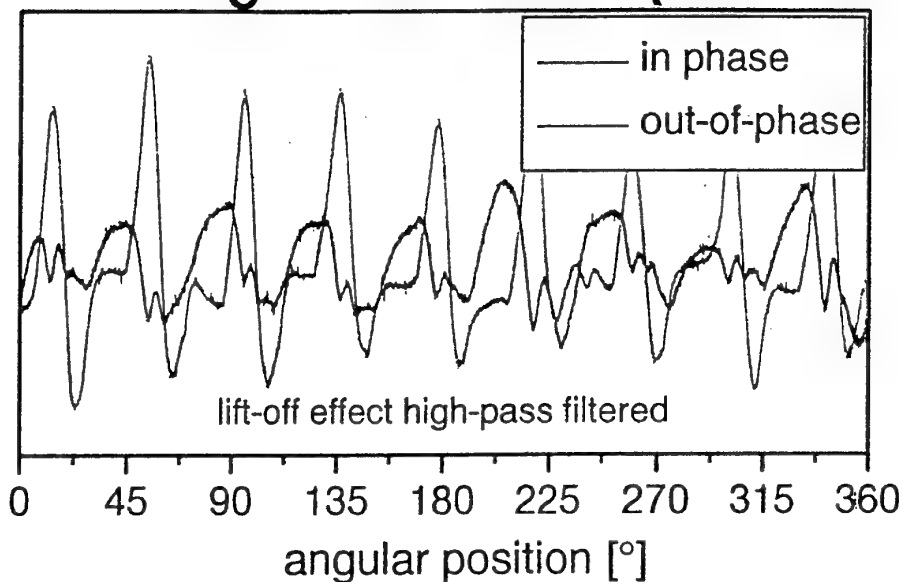
Mobile Cryostat for SQUID cooling (ILK Dresden)



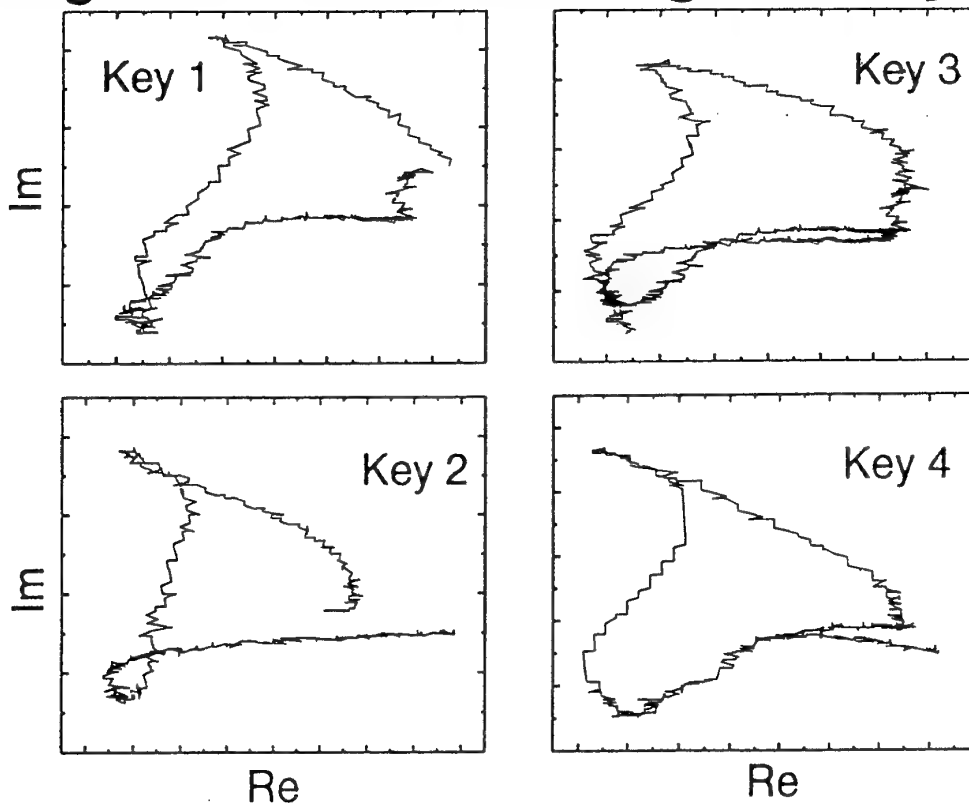


Flawless Airbus wheel

Lock-in signal of SQUID (one trace)



Signature from ferromagnetic keys

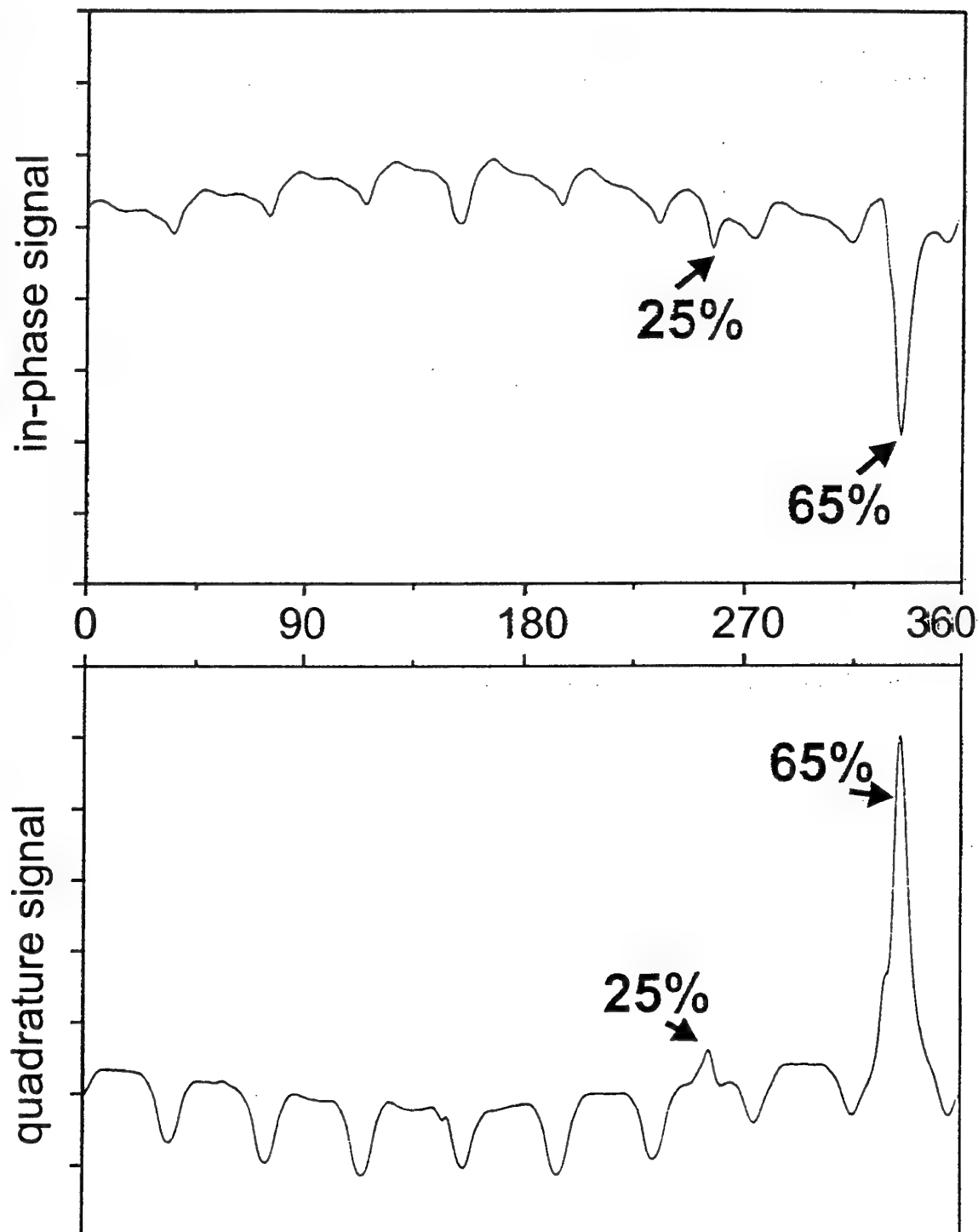




Aircraft Wheel Testing

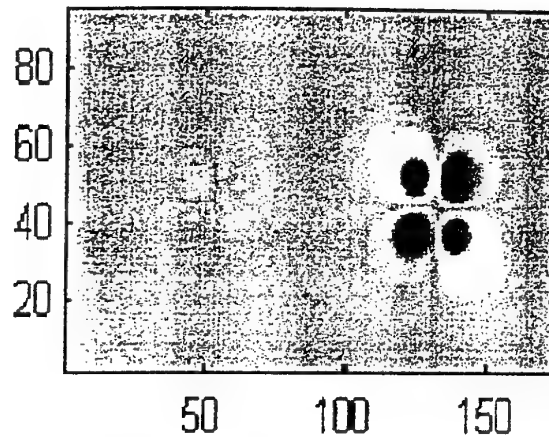
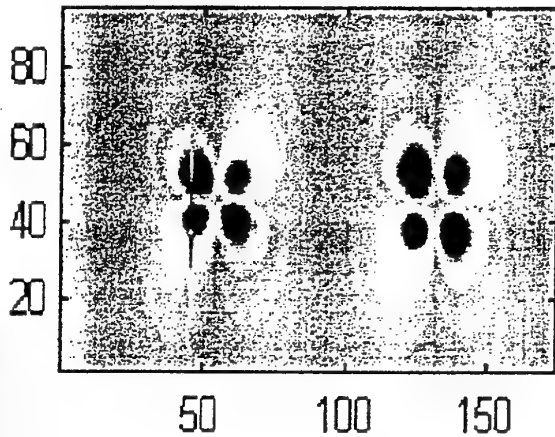
rf-Gradiometer, $f = 215 \text{ Hz}$, $I = 200 \text{ mA}$

trace with 65 % crack and 25 % crack



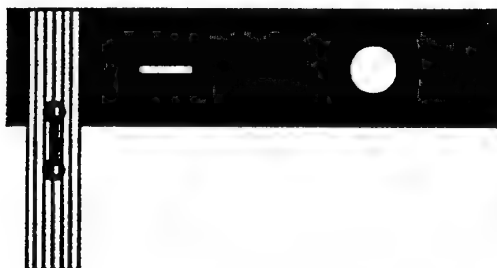
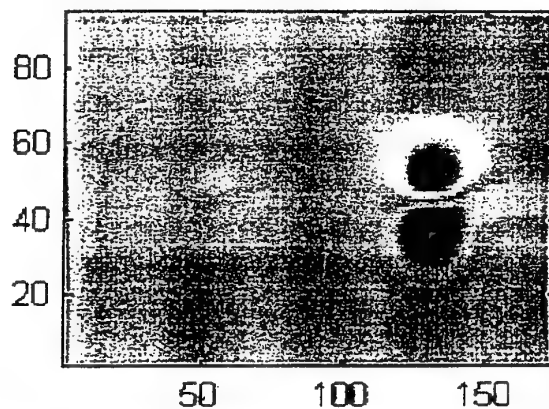
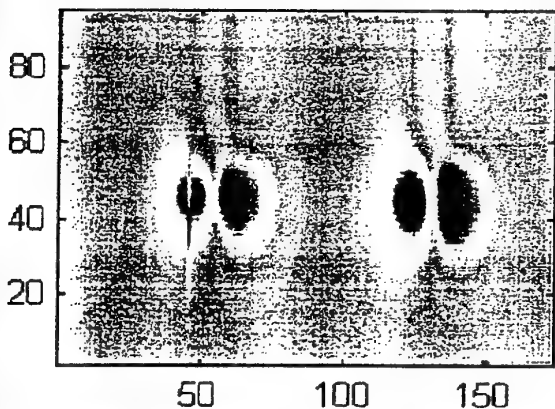


Orthogonal Excitation with Planar Gradiometer and Sheet Inducer



↑ Signal

↓ integrated along gradiometer baseline



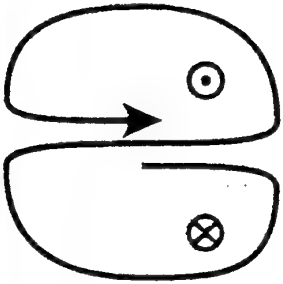
aluminum plate
(250×250×4mm³)
with 12.5mm slot
and 12.5 mm hole

Sheet inducer with planar rf gradiometer

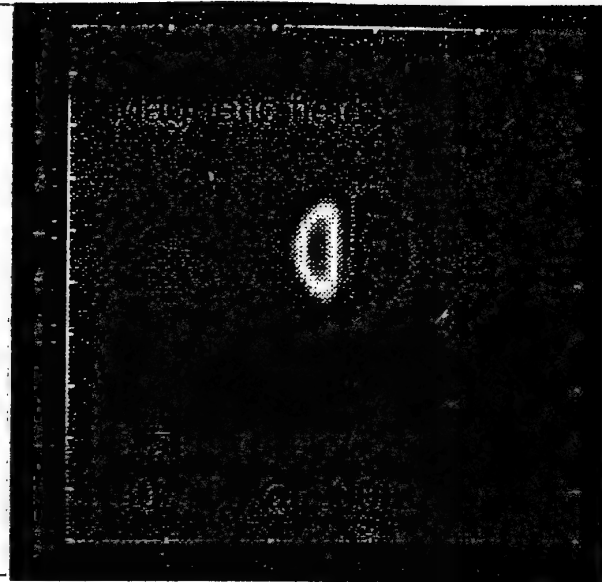
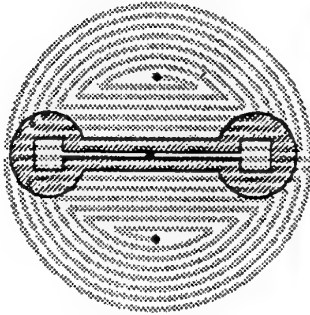
Excitation current: 5 mA @ 500 Hz

a) Multi-D coil

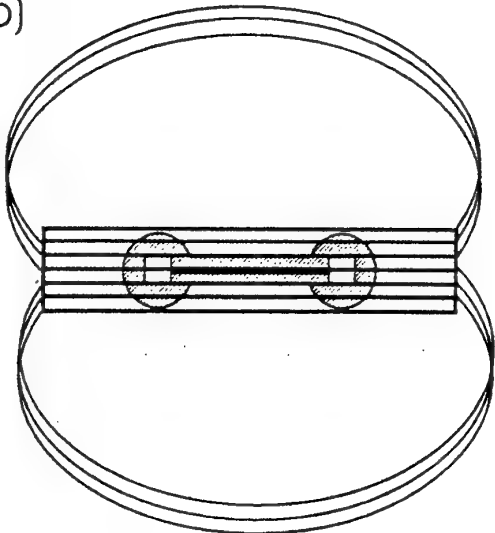
Principle



Setup with Gradiometer



b)



Sheet Inducer

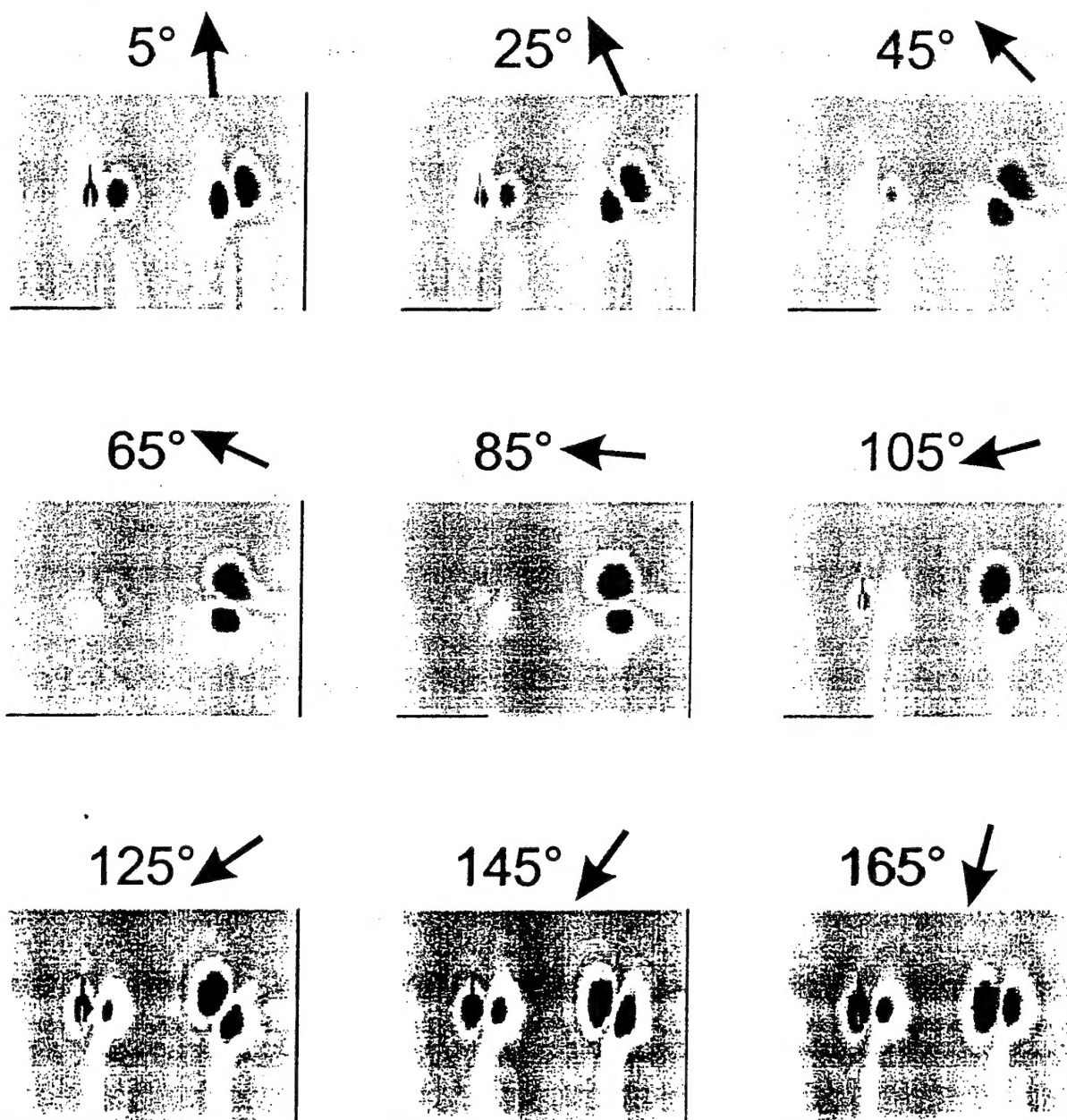
Setup with Gradiometer

Fig. 6: MULTI-D COIL AND SHEET INDUCER
WITH SQUID SETUP



Rotation of excitation current

Software Evaluation of Orthogonal Measurements
with Planar Gradiometer and Sheet Inducer



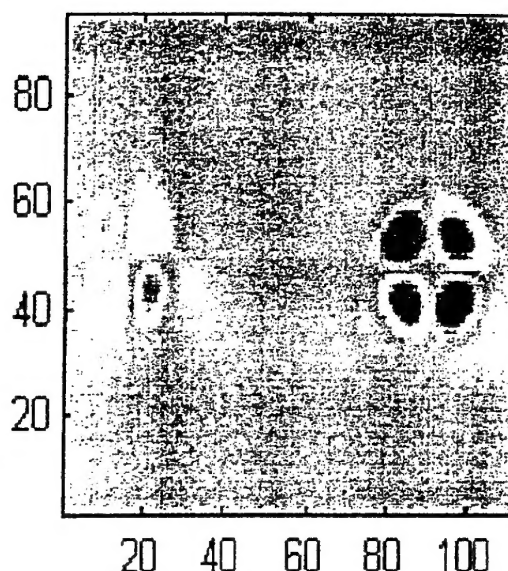
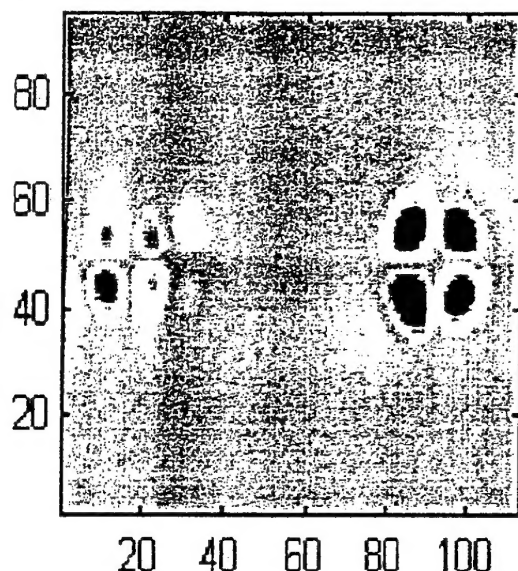
Excitation: 5 mA @ 500 Hz

aluminum plate (250×250×4mm³)
with 12.5mm slot and 12.5 mm hole



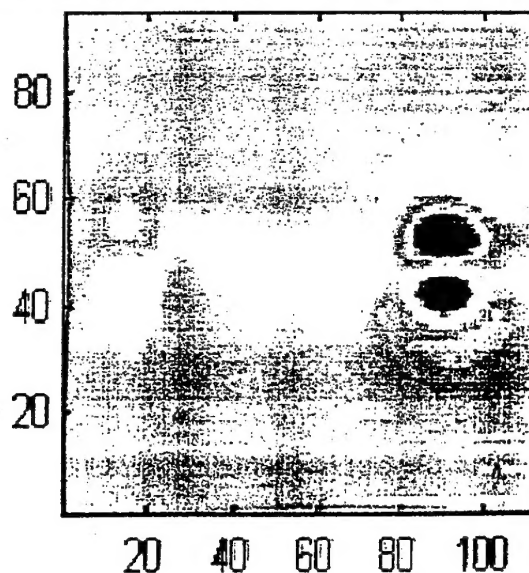
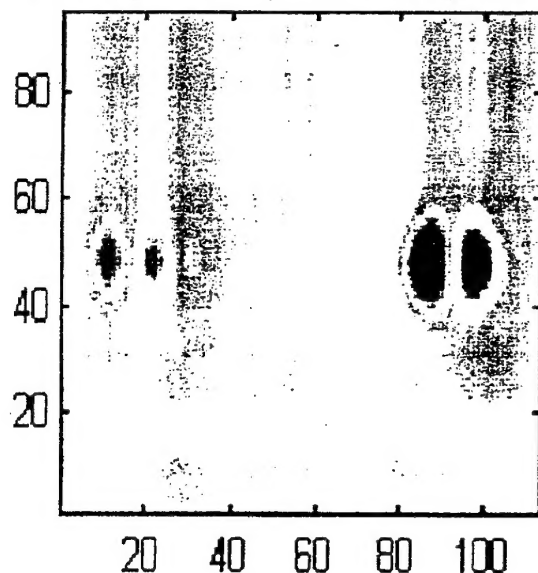


Orthogonal Excitation with Planar Gradiometer and Multi-D Coil



↑ Signal

↓ integrated along gradiometer baseline



Multi-D coil with planar gradiometer

Excitation current: 1 mA @ 500 Hz

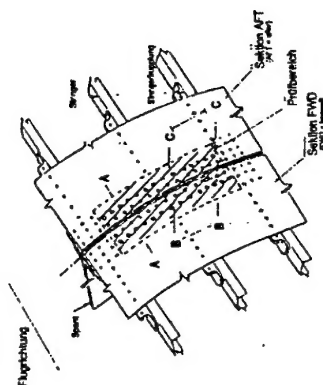
aluminum plate
(250×250×4mm³)
with 12.5mm slot
and 12.5 mm hole



SQUID measurement of DASA Calibration Sample

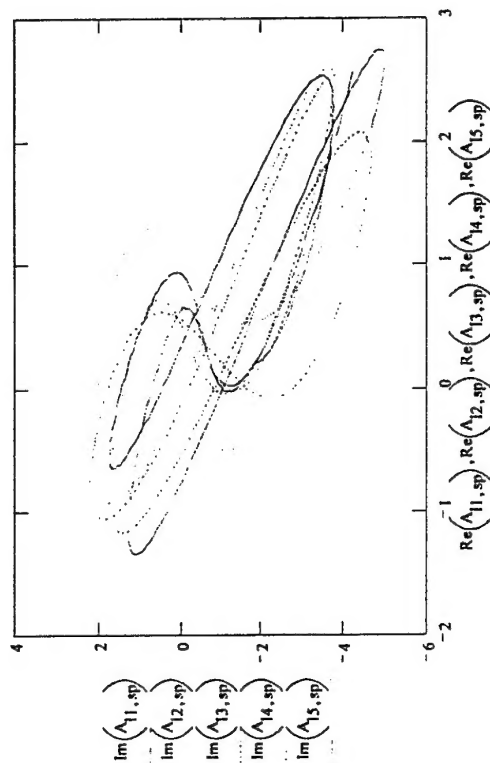
Rivet distance: 25 mm
Rivet diameter: 4.8 mm

Section FWD

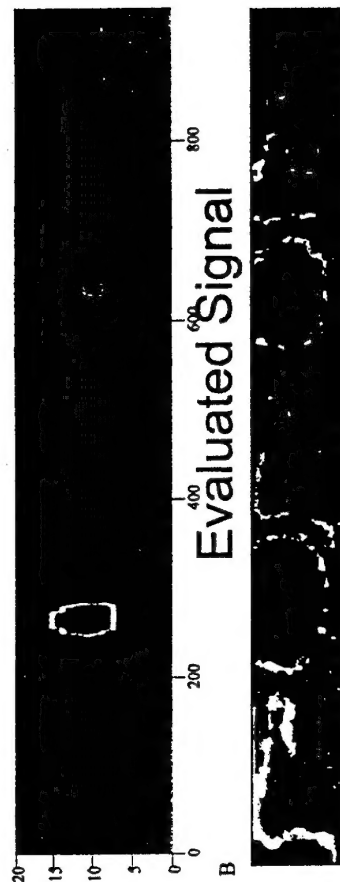


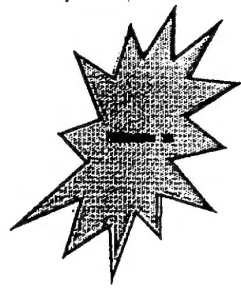
●	13	11mm	●	14	5.6mm	●	15	8mm	●	16	1.9mm	●	17
---	----	------	---	----	-------	---	----	-----	---	----	-------	---	----

15 190 (k 4)..190 (k 5) 1



Conventional measurement:
(Eddyscan)





Harold Weinstock (AFOSR) - 1997

“Those of us who are seeking potential SQUID NDE applications would do well to spend more time at NDE meetings. At these meetings we will learn what the real problems are, and how far we must go to outperform the existing and emerging competition. Furthermore, we must visit manufacturing and processing plants to learn how a SQUID might be used to speed production and improve quality control. The results of such forays into the world of NDE will have a major impact on the future of SQUID technology.”



Harold Weinstock DHC, INSA Lyon 1999